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Work-in-Progress: Chemical Engineering Students' Representational Fluency when Designing in the Context of Fluids Mechanics

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Abstract

Incorporating design into the engineering curriculum has become an educational priority, as it significantly influences students' learning, motivation, and development of an engineering identity, among other outcomes. While some research exists about the teaching and learning of engineering design in the first- and last- years of undergraduate education, the second and third years have received comparatively less attention. This study contributes to this gap by exploring the design practices of third-year chemical engineering students. Particularly, it focuses on students' ability to create and translate among multiple representations (i.e., representational fluency) as an essential engineering analysis and design ability. We ask: *How do third-year chemical engineering students create and translate across multiple representations when working on a design project in the context of fluid mechanics?* We used a qualitative research approach to explore the representations employed by four student teams working on conceptualizing a sustainable and safe fuel storage tank and delivery piping system for an Air Force Base (fictitious client). They completed the project as part of their fluid mechanics course requirements. We coded the five project deliverables using a co-evolution framework of the engineering design process and an adapted version of the Lesh Translation Model, a framework for representational fluency. For this work in progress, we present the results of one of the teams composed of four chemical engineering students. Our initial results showed that the students created or downloaded images and wrote text to communicate their framing of the problem and solutions. However, the students needed scaffolding to translate those representations into symbolic mathematical models. They did not intuitively develop models to test and make decisions. Furthermore, they needed additional support to integrate information from the sociotechnical context into their framing.

Introduction and Theoretical Framework

Professional engineers apply various skills and practices when dealing with complex, open-ended, and ill-structured problems (i.e., design problems) in the workplace. One of the most important ones is representational fluency, which is defined as the practices and skills associated with creating, using, interpreting, and translating among multiple external representations [1], [2], [3], [4], [5] such as diagrams, sketches, mathematical expression, simulations, physical models, etc. Some argue that engineers' work is all about using representations in a sociotechnical context [6], [7]. Engineers' representational fluency allows them to reason with external representations, share a common understanding of the design situation, collaborate, and communicate ideas [1], [8], [9]. Furthermore, representations are essential when working on design problems to represent ideas or prototype solutions [10], [11], [12]. For instance, Bucciarelli [8] identified that engineers use external representations or artifacts, such as matrices of concepts or block diagrams, as bridges to facilitate communication and collaboration across disciplines.

Although representational fluency is a demanded skill for engineers, previous studies have shown that undergraduate students may struggle to generate, coordinate, and generally handle multiple external representations [9], [13]. For instance, Carberry & McKenna [13] found that students do not realize the full power that models and modeling can bring to design, and they recommended explicit instruction of modeling in formal engineering education. The engineering curriculum needs to support students' development of representational fluency better.

Appropriately integrating sociotechnical design problems into the curriculum can support students' development of engineering skills, practices, and conceptual understanding while also learning design [14], [15]. Sociotechnical problems are design problems that include social and technical constraints [16], [17]. Addressing sociotechnical problems reflects the professional workplace in which engineers typically address and solve engineering problems that merge social and technical constraints [8], [16], [18]. By exploring the students' representational practices and skills, we can design appropriate scaffolds that support them in developing expertise. This research aims to examine chemical engineering students' representational skills and practices when dealing with sociotechnical design problems. Mainly, we ask:

How do third-year chemical engineering students create and translate across multiple representations when working on a sociotechnical design project in the context of fluid mechanics?

We theorize students' design process following a co-evolution approach. Instead of perceiving designing as an algorithmic problem-solving process similar to the mathematical problem-solving process, we conceive of the design process as an iterative exploration of a design space composed of problem and solution spaces [19], [20]. This exploration continues until the designer identifies an appropriate problem-solution match. Namely, our engineering students iteratively frame their engineering problem (i.e., problem space) and envision solutions (i.e., solution space) from the beginning and throughout the design project. The exploration of the problem and solution spaces happens through three mechanisms: analysis, synthesis, and evaluation [21]. Students analyze problems or solutions to clarify their features. Students synthesize new problem elements to expand or decompose the initial problem and synthesize aspects of solutions when developing new ideas or novel combinations. Students use evaluation to assess their understanding of the problem and the appropriateness of their solution given the design context.

Students use multiple external representations while exploring the design space of their engineering projects through analysis, synthesis, and evaluation. We term representations broadly as any "artifact" created or used by the students when addressing their engineering design projects. We categorize the properties of those representations according to their possible media using the characterization of Lesh and Doerr [22] as pictorial representations, concrete models, written and verbal language, and symbolic representations. For example, engineering students could sketch an idea, which we would characterize as a pictorial representation of a solution entity. Our aim was to use these theories to *characterize* chemical engineering students’ representational skills and practices—not evaluate the quality of their solutions.

Methods

In this work-in-progress, we report an exploratory qualitative study investigating students' representational fluency in an engineering design project context.

Participants and setting

Following IRB approval and informed consent procedures, we conducted this study in a required, 3-credit, junior-level, fluid mechanics and heat transfer course in a chemical engineering department at a Hispanic-serving research university in the Southwestern United States. Seventeen students consented to participate.

This study focused on the first part of the course, where students learned fluid mechanics. The instructional team included a chemical engineering professor, a postdoctoral scholar with a background in chemical engineering and engineering education (the first author), whose focus was mainly on the design project, and an undergraduate chemical engineering student who supported grading and tutoring. The course met three times a week. Instruction included lectures, problem-solving sessions, and weekly homework covering fluid statics, ideal and viscous fluids models, and steady-state and time-dependent fluid flow problems, among other concepts. Throughout the semester, students worked in randomly-assigned teams of three to four. They completed deliverables related to an engineering design project called "Bulk Fuel Facility for the Kirtland Air Force Base," detailed next. The teams' design project deliverables became the primary data for this study.

Engineering design project: New bulk fuel facility for the Kirtland Air Force Base

The engineering design project tasked students to develop a new, sustainable, safe fuel storage tank and delivery piping system for the Kirtland Air Force Base (KAB). The context was locally familiar for students, some of whom completed internships on base, and there was the largest toxic spill in the United States [23]. The design brief included as constraints the following:

- Come up with a sustainable and safe fuel storage tank and delivery piping system for the KAB (provided map to the students).
- The tank should store 250000 gallons of Jet-Propulsion Fuel 8.
- The piping system should ensure the fuel is received and appropriately delivered to the hangar area free of contaminants and in a reasonable time.
- The design must include technical specifications (e.g., materials, storage tank capacity, flow rate through the delivery piping system, pipe diameter, fluid velocity, flow regime, etc.) and safety specifications (e.g., time to detect X amount of leaking, maximum capacity for containment, how much fuel can be contained when leaking, etc.).
- The technical report must describe assumptions, limitations, and possible adverse effects of the construction on the base's operations, environment, and nearby communities and how they could be minimized.

The project included five deliverables (refer to Table 1), through which, the instructional team scaffolded students' progress and providing feedback. In the first deliverable, the teams conducted a literature review to start framing their problem by characterizing the client and stakeholders and identifying additional legal, technical, social, and environmental constraints. The teams analyzed, synthesized, and evaluated new fuel storage tanks and delivery piping systems along with their initial list of constraints and stakeholders in deliverables two to five. Deliverables two and three explicitly required the teams to come up with pictorial representations of their solutions (sketches, process flow diagrams, layouts, etc.), and deliverable three emphasized the usage of symbolic representations. Namely, the teams were required to develop a mathematical model to characterize and evaluate their proposed bulk fuel facility. Finally, deliverables four and five focused on instructor and peer feedback based on the teams' oral presentations and written technical reports.

Table 1. Design project deliverables.

No.	**Main Tasks**	**Expected Representations**
1	• Look for literature on the design of bulk fuel facilities. • Identify the project stakeholders. • List legal, technical, and social/environmental requirements. • Identify potential trade-offs for the requirements.	• Written language
2	• Write a problem statement. • Revise the requirements list based on feedback. • *Configuration ideation:* Ideate 3 tank and piping configurations based on found technologies using written descriptions, sketches, layouts, and diagrams. • *Equipment ideation:* Choose two configurations and propose possible parameters for the equipment (e.g., tank shape and dimensions, materials, energy requirements, etc.). • *Design testing:* Using the identified requirements, evaluate the two possible configurations with their equipment details. • Reflect on the design process.	• Written language • Pictorial representations • Symbolic representations (Numbers)
3	• Revise the problem statement and requirements list. • Model 1 idea using the KAB map and additional pictorial representations. • Use mathematical modeling to develop the idea further. • *Design testing:* Evaluate the model using the identified requirements. • Reflect on the design process.	• Written language • Pictorial representations • Symbolic representations (Numbers and equations)
4	• Present the problem-framing process and describe the solutions for instructors and peer feedback.	• Written and oral language • Pictorial representations • Symbolic representations (Numbers)

5	• Revise the problem statement and requirements list. • Write a technical report summarizing the design process. • Propose recommendations for the client to reduce costs and mitigate unintended adverse effects. • *Design testing:* Evaluate the two possible solutions using the identified requirements.	• Written language • Pictorial representations • Symbolic representations (Numbers and equations)

Data collection and analysis

We collected the five engineering design project deliverables from the entire class (four teams) as the primary data for this project. To better comprehend the students' experience, the first author observed all classes, tutored students in problem-solving skills related to fluid mechanics, and revised and evaluated the project deliverables. Finally, we also collected the class slides, exams, and homework as complementary data.

We inductively analyzed the teams' deliverables to characterize their representational fluency. The first author carefully read all teams' deliverables and identified that students created or used primarily three representational modes: written descriptions, pictorial representations (diagrams, pictures, sketches, etc.), and symbolic representations, including numbers and mathematical expressions. Based on that, he met with the second author, reviewed the teams' deliverables, and decided to analyze the teams' representations using the procedures described in Table 2.

Table 2. Analysis procedures for the main representational modes found in the students' deliverables.

Representational Mode	Analysis Procedure
Written information	Read the teams' descriptions of the problem and solution elements, including constraints, stakeholders, justification for their design decisions, etc. It focused on team claims, evidence of the problem and solution framing, and their changes throughout the five deliverables.
Pictorial representations	Analyzed images, sketches, and diagrams. It focused on the purpose of the pictorial representation, the features shown or omitted, and their changes throughout the five deliverables.
Symbolic representations	Analyzed numerical values and mathematical models. It focused on accuracy, the purpose of the models, and changes throughout the five deliverables.

The two researchers analyzed and discussed the team's written, pictorial, and symbolic representations in detail. For the current work-in-progress study, we chose to present the results of one team of four students (two men and two women) in order to examine their various representations in detail. We specifically selected a focal team because they received average scores throughout the project deliverables and, based on review of all teams' work, their deliverables illustrate the kinds of representational shifts observed. We consider this approach a necessary step enroute to developing a comprehensive approach to analyzing data from a larger corpus, including students from future iterations.

Preliminary Findings

The team successfully created a conceptual design for a Bulk Fuel Facility for Kirtland Air Force Base. The assignment instructions prompted them to synthesize, analyze, and evaluate problems and solutions using pictorial, symbolic, and written representations.

In Deliverable 1, the team started framing and understanding the design problem and represented it using only written language. They sought and summarized the literature on current technologies for storing and transporting fuel, strategies for leak detection and containment, legal requirements in constructing bulk fuel facilities, and possible environmental and community health risks associated with fuel leaking. Based on that information, they constructed an initial shared model of the design problem represented in a list of stakeholders and requirements. The team identified stakeholders as the nearby communities, manufacturing companies, technical personnel, engineers, and architects and described stakeholders' connection to the problem. For example, they explained that nearby communities are affected: "Nearby population is negatively affected by contaminated water. The people in this community are at risk for diseases, cancers, and other health effects should a spill reoccur." This initial definition of stakeholders simplifies the contextual information, as some populations could be more affected by a spill. Looking for a deeper understanding of the problem and construction of a more accurate model of the design context, the instructors scaffolded the team to think more in-depth about the design context. By the last deliverable, the team specifically characterized the impacted communities as "including the communities of Sandia National Laboratories, the Albuquerque International Sunport, and those in nearby neighborhoods."

Regarding the requirements, the team identified legal, technical, social, and environmental requirements of the design problem. Table 3 summarizes the requirements the team defined in their first and last deliverables. The list of requirements served as an external written representation of the team agreement of what is relevant for the design and what they need to focus on. Based on the initial requirements, the instructors realized, for example, that the team was not considering variables associated with the fuel flow regime, which is central to the Fluid Mechanics course. Throughout the analysis and evaluation of the requirements in the subsequent deliverables, they synthesized as requirements the flow rate of fueling, the fueling efficiency, and the tank storage capacity.

Table 3. Requirements defined by the students' team in their first and final deliverables.

Type	Initial Requirements	Final Requirements
Legal	Steel performance	Steel Performance
	Secondary containment	Secondary Containment
	Corrosion protection	Corrosion Protection
	Piping protection	Piping Protection
Technical	Periodic test for leaks in the system	Periodic test for leaks in the system
	Automatic gauge system	Flow rate of fueling

	Tank physical and mechanical properties	Tank physical and mechanical properties
	Pipe leak detection	Pipe leak detection
		Fueling efficiency
		Tank storage capacity
Social/ environmental	Plan for failure	Plan for Failure
	Storage of materials	Storage of Materials
	Environmental testing	Environmental testing
	Noise level	Noise Level
		Tank and piping maintenance and cleaning
		Tank and pipe materials sustainability
		Construction effort versus time

The written description of the requirements may have supported the team to create a shared understanding of the design context. This process can be challenging for teams due to the limited access to direct observations of the KAB facilities. Namely, in a real engineering design job, in addition to a literature search, professional engineering designers would visit the site, take pictures, and talk with stakeholders to better understand the design context. In contrast, the team had to create a similar workable model of the KAB context based only on their literature search. They represented the design problem with written language but used a greater variety of representational modes when working on the solution space, as detailed in the following paragraphs.

The team presented their first pictorial representations in Deliverable 2 while ideating new fuel storage and piping delivery systems for KAB. As prompted by the deliverable instructions, the team devised three possible solutions and represented them using diagrams, sketches, and written descriptions. Figure 1 depicts three pictorial representations (sketch, process flow diagram, layout) used by the team to express their first design. Table 4 summarizes the team's initial and final design parameters defined according to the design prompt, their literature search, negotiations, and mathematical modeling. The pictorial representations showed the main elements of their idea (pumps, storage tank, fueling area, pipes, etc.) using symbols and omitting constraints of KAB, such as the location of the new facility or the available construction area. Since the project is part of a chemical engineering course, they may have decided to focus on showing decontextualized representations of their ideas that explain the idea functionality with less context information. Furthermore, some students were surprised when the instructors recommended integrating more context into their solutions. They thought that would be outside of the project scope. Integrating the context would add more variables to the problem and require a better analysis of the problem space, making the design project more complex.

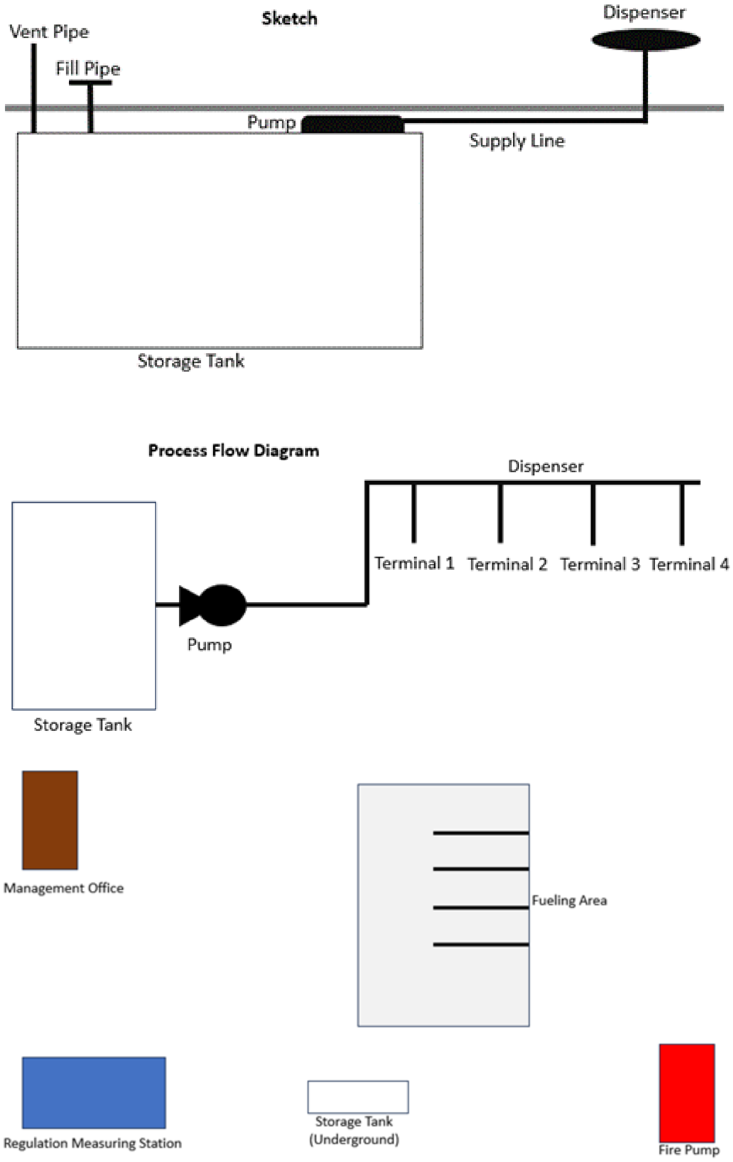

Figure 1. Pictorial representations of the first solution element proposed by the team.

Table 4. Initial and final solution parameters defined by the students' team based on their design space exploration.

Item	**Initial solution element**	**Final solution element**
Tank	• 1 underground storage tank • Material: Carbon steel • Volume: ~252000 gal • Dimensions: Shape: Cylindrical Diameter: 9m High: 15m	• 6 underground storage tanks • Material: Carbon steel • Volume: ~250000 gal • Dimensions: Shape: Cylindrical Diameter: 3.048m High: 21.64m
Pipeline	• Underground piping: • Outer layer: Steel	• 2 pipeline systems: Venting system

	• Inner layer: High density polyethylene (HDPE) • Diameter: 0.12-0.15m • Wall thickness: 0.438 – 0.544 m • Material: Epoxy fiberglass pipe .	Fuel flow system • Underground piping • Outer layer: Steel • Inner layer: High density polyethylene (HDPE) • Length: 25m per tank • Diameter: 0.5m • Fluid flowrate: 2 m/s • Bulk flowrate: 0.026 m^3/s • Flow regime: Turbulent
Leak detection and containment	• Berm containment: Length: 30m Width: 30m High: 5m Material: PVC polymer-based geomembrane • Automatic Gauge tank system with Veeder-Root	• Berm containment: Length: 15m Width: 10m High: 5m Material: PVC polymer-based geomembrane • Automatic Gauge tank system with Veeder-Root Detect 0.2 gallon/hr leak

By the third deliverable, the team analyzed and evaluated their preliminary designs; then, they chose and further developed one idea. The deliverable and instructor feedback prompted the team to better integrate the KAB context by creating different models of their solution and defining the specific location of the new facility inside the KAB. Figure 2 shows the pictorial representations of the team's idea and the facility location. The team used pictorial and symbolic representations as low-fidelity prototypes to analyze and evaluate their solution in this deliverable. Specifically, they mentioned in their report:

> "Multiple representations can help validate our design. Each representation (visual and mathematical) supports each other. The visual representation is a proof of concept, while the mathematical model shows the feasibility of our design choice."

For example, the team used the map to identify the size of an available construction area and evaluate if the tanks would fit in that space. Also, they determined possible paths for the pipelines and assessed using a truck to move the fuel from the storage area to the hangar.

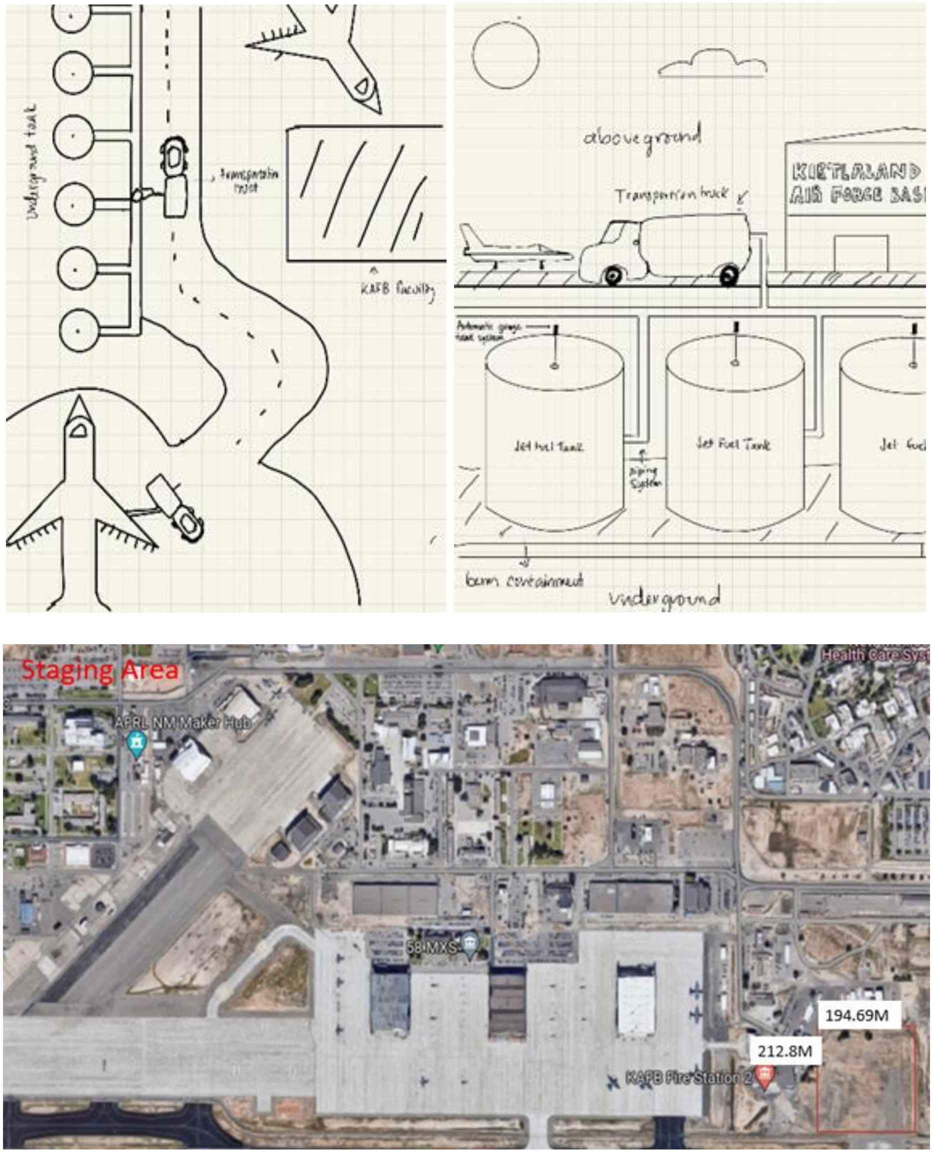

Figure 2. Intermediate pictorial representations of the team's solution.

In contrast with the team's representations in Deliverable 2, in Deliverable 3, they seemed to highlight less the functionality of their system and more the layout and design context (see Figure 1 versus Figure 2). For example, they emphasized changing a previously proposed single large tank to six smaller tanks and integrating fuel trucks to transport the fuel from the facility to the hangar. There seemed to be a tension between engineering design and engineering analysis. The team needed to decide what to depict and focus on the system's main elements using abstract symbols like in Figure 1 (Deliverable 2) or a more realistic representation of the system like the one presented in Figure 2 (Deliverable 3).

In addition to pictorial representations, the team tried to model their solution mathematically to identify additional design parameters. In this process, they started proposing questions about their design that could be answered through mathematical models (See Table 5). These initial questions aimed to help students move from the real design context into the abstract mathematical models, which students typically find complicated. The team successfully identified questions that included fluid mechanics topics (e.g., pressure loss, laminar or turbulent flow, flow rate, etc.). Furthermore, when asking, "How does answering the question improve your design," the team indirectly connected the question with design requirements.

Table 5. Questions proposed by the team to improve their design using mathematical modeling.

Question	How does answering the question improve your design?
Is the fuel flow through the pipeline laminar or turbulent?	Determine fuel pressure loss.
How many tanks are to be used?	Determine fueling efficiency and safety.
How much volume can the tank hold?	Determine fueling capacity.
How long is the piping system from the tank to the fueling center?	Determine energy and monetary costs for our system.
What is the energy requirement to maintain the electronic systems?	Determine energy and monetary costs for our system.
What is the adequate flow pressure/ velocity for fueling?	Determine the longevity of the system, design safety, and dimensions of the design.
How long can the secondary containment system hold leaks?	Determine how fast the system needs to be able to detect leaks and how fast we need to respond to said leaks.

Although the team could identify potential areas to apply mathematical models, they struggled to develop their ideas into mathematical models in Deliverable 3 fully. One of the chosen questions by the team was "What is the energy requirement to maintain the electronic systems?" which was outside the scope of the class. They answered the solution by focusing on the required energy to run the automatic sensing system and using the equation:

$$\text{volts x amps} = \text{watts (joules/sec)}$$

They used the technical information of the sensing system to determine that the system would require from 160 to 320 W. In addition to this question, they tried to solve the question "What is the adequate flow pressure/ velocity for fueling?" which is closer to the class topics. However, they tried to answer it using mathematical models found in a research article that were not covered in class. The team or the person working on the mathematical modeling may have struggled with the class topics. They could have lacked confidence or not know how to apply the class models to the design problem. Interestingly, all students had solved simplified fluid mechanics problems with the context of the KAB as part of their homework, but they did not use them in their Deliverable 3. We will further investigate how the students connected the homework problems that focus on problem-solving with the modeling process of their proposed solution.

The team modeled their final solution using written descriptions, pictorial representations, and symbolic representations in the final presentation and technical report. Figure 3 shows the final pictorial representation made by the team. This representation tried to balance the engineering design and analysis by including details about the functionality of the system and the design context. Namely, the team drew a fuel truck to show how the fuel would be transported, and they included tank systems with venting and fuel piping systems and pumps. The representation allowed the team to construct a co-sharing understanding of the design situation that they could manipulate to create a solution. Figure 3 shows the team using the representations to understand the problem and solution in that term. More accuracy would be needed if the representation served the purpose of communication. For example, the representation could better use the perspectives of the system. There is a mixture of frontal views and isometric perspectives.

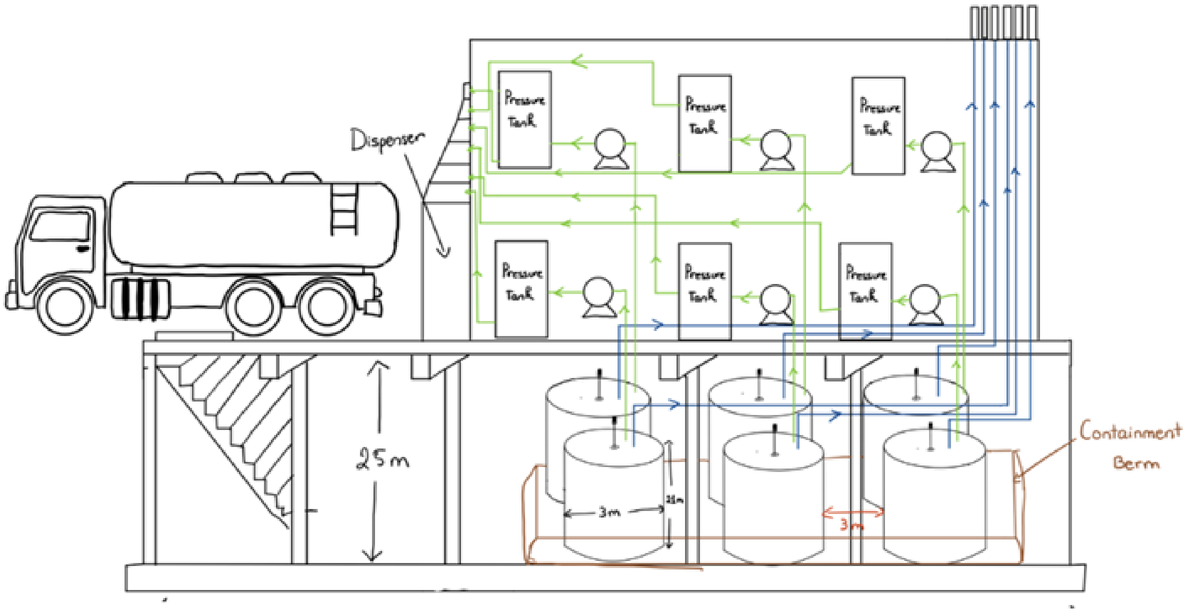

Figure 3. Final pictorial representation of the team design.

In terms of modeling, the final deliverables explicitly requested students to calculate, as a minimum, the fuel flow rate, fluid velocity, flow regime, and energy requirements to move the fuel from the tank to the destination. For the final report, the team removed the calculations associated with the energy of the electronic system and calculated the rest of the parameters successfully. Table 3 summarizes the final parameters of their design.

Limitations and Future Work

Our approach provided a detailed illustration of one team's representational fluency development, which corresponds with the kinds of representational shifts observed in the other teams' work. This effort provides a proof of concept for characterizing third-year chemical engineering students' representational fluency when working on a sociotechnical design project in the context of fluid mechanics. In our ongoing work, we plan to extend our study to include another iteration in the upcoming semester, using the framework illustrated in this work-in-progress study.

The current study also has several limitations that can be addressed in future studies. Since we only had access to the teams' deliverables, we could not explore how students create or collaborate with multiple representations. Future studies could explore team dynamics while developing project deliverables to provide a more complete understanding of their representational fluency. Additionally, we will examine strategies to scaffold students' integration of the design context into their solutions and successful usage of mathematical modeling.

Acknowledgments

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