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# An Engineering Clinic-Based Approach to Teaching Process Design and Modeling: Bridging Theory and Practice

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## ABSTRACT

Advancing student understanding of process design requires a balanced integration of theoretical knowledge with real-world industrial applications. This study introduces system design thinking-based learning through an engineering clinic approach that bridges the gap between classroom concepts and chemical engineering practice. Using an industrial multiproduct oil pipeline operation as a case study, students are exposed to real-world industrial systems, identify bottlenecks in a process, draw similarities between systems at different scales, and implement control strategies to address a practical industrial problem. In this study, we highlight the collaborative efforts between faculty, students, and industry partners to provide experiential learning in process design, modeling, and control to address the challenge of minimizing product loss during flushing operations in multiproduct petroleum pipeline systems.

**Keywords**: Dynamic Modelling, Fluid Dynamics, Process Design, Flushing, System Identification

## 1. INTRODUCTION

### 1.1 Motivation

The chemical industry is vast, spanning more than 70, 000 products, including ceramics, food, fuels, industrial gases, petrochemicals, pharmaceuticals, plastics, and textiles [1]. Recent advancements in chemical engineering practices have evolved towards increasingly integrated, complex, and data-rich systems operating under tight economic, thermodynamic, environmental, and safety constraints. Modern process industries require engineers who can reason across interconnected systems, predict dynamic interactions, and make informed decisions under uncertainty and variability [2]. Consequently, there is a growing need for systems and holistic design thinking approaches in both industrial practice and engineering education.

### 1.2 Gap in undergraduate process design and modeling instructions

Despite the shift in modern industrial practices, many undergraduate courses in process design and modeling often remain fragmented. Process design is typically taught as a capstone experience focused on steady-state analysis, equipment sizing, safety, and economic evaluations. Process modeling, on the other hand, is often introduced in the curriculum, with an emphasis on mathematical formulation and analytical solution techniques. Although each course addresses essential competencies, the lack of explicit integration can limit students' ability to understand how design decisions influence the dynamic behavior, operability, and optimization of real processes. Considering the traditional process design and modeling curriculum, students are frequently exposed to modeling in abstract contexts, with limited opportunities to validate models against physical systems and experimental data. In addition, modeling instances for some students is regarded as a purely mathematical exercise rather than a decision-support tool [3].

This disconnect is evident when students encounter industrial problems that do not conform to textbook assumptions. Real systems are subject to transient behavior, nonideal mixing behavior, uncertainties in measurements, equipment limitations, and complex operational constraints and performance objectives [4]. In such contexts, mathematical models alone are not sufficient; engineers continuously validate theories with experimental data, revise assumptions, and evaluate trade-offs to refine established mathematical models to capture the entire system behavior. Traditional coursework often relies on well-defined problems with complete information and predetermined solutions. In contrast, industrial problems are typically constrained by incomplete data, uncertainties in measurements, design flaws, practical limitations, and operational inefficiencies, as in the case of trial-and-error in most industrial applications.

Thus, it highlights the importance of systems design thinking, an approach that emphasizes understanding interactions among system components, recognizing feedback and nonlinearities, and iteratively refining solutions based on data and constraints. Systems design thinking expands beyond component-level optimization of processes to systems-level performance, enabling students to reason about cause-effect relationships, nonlinearities, and uncertainties associated with processes. This is a critical aspect in chemical engineering because of the coupled nature of process units, material properties (physical, chemical, structural, and thermodynamic), control strategies, and operational decisions and constraints.

### 1.3 Contributions of systems-oriented process education

This paper presents a systems-oriented, engineering clinic-based approach to teaching process design and modeling. The approach integrates systems design thinking with engineering clinics and project-based environments, emphasizing the direct application of classroom concepts, design, experimentation, and system-level decision-making.

The contributions of this study are threefold. First, this study articulates a structured engineering clinic framework that embeds systems design thinking into the undergraduate curriculum. The framework emphasizes problem identification, experimental setup, stem boundary definitions, and trade-off analysis, enabling students to think holistically about complex processes. Second, it demonstrates how engineering clinics and project-based learning can be used to operationalize this framework through collaborative, industry-inspired problem-solving that mirrors professional industrial practice. Finally, a case study is introduced to demonstrate how pilot-scale experimentation and modeling efforts can be integrated to support iterative design refinements and operational optimization. These contributions are demonstrated through an industrially motivated case study focused on minimizing product loss during flushing operations in petroleum pipelines. The case study requires students to integrate fluid dynamics, process scale-up and scale-down, mixing behavior, experimental analysis, and modeling to minimize product loss, operational downtime, and enhance overall operational productivity.

## 2. SYSTEMS DESIGN THINKING LEARNING APPROACH

### 2.1 Motivation for systems design thinking

Process design and modeling are inherently system-level activities. Teaching these concepts requires students to operate at multiple levels of abstraction, often simultaneously. Students must reason from physical intuition to mathematical representation, from component to system-level performance, and from theoretical concepts to practical design decisions. The systems design thinking framework addresses the challenge of the traditional approach to process design and modeling by structuring how students connect, organize, and apply classroom knowledge during design processes and decision-making. Rather than treating design as a culminating activity that follows analysis, the framework positions design thinking as a principle that integrates modeling, design, analysis, and experimentation. This strategy supports cognitive learning [5] by helping students develop mental models of how process units and signals interact and how design decisions propagate in real systems.

Process design and modeling are rarely linear activities; assumptions evolve, models are refined, and design objectives are revisited based on newly acquired data. Thus, systems design thinking legitimizes this iteration as a core learning activity, urging students to treat design, modeling, and experimentation as complementary tools for understanding and improving system performance. This approach mirrors the way engineers approach complex industrial problems. Hence, students learn not only how to model or design a process, but also why a particular modeling approach is appropriate, what its limitations are, and how it informs design decisions. In essence, systems design thinking serves as a bridge between foundational engineering science and real-world design practice. The framework provides students with a repeatable cognitive strategy for navigating complexity, enabling them to approach complex and new problems with confidence, adaptability, and engineering decision-making.

### 2.2 Engineering Clinic-Based Approach

#### 2.2.1 Concepts of engineering clinics

The engineering clinic program provides a sustainable approach to engineering education that fosters an understanding of theoretical concepts and their application. This is deeply rooted in the top skills defined by the World Economic Forum for being a great engineer. These skills include critical thinking, creativity, people management, problem-solving, and teamwork [6]. A defining feature of the engineering clinic program is its integration with the core concepts of systems design thinking. Within the clinic projects, students are introduced to an authentic context where systems design thinking can be practiced, tested, and refined.

The engineering clinic program is a hallmark of the undergraduate curriculum at Rowan University. Students are introduced to the clinic program early on, thus spanning the first to final year of their educational journey. Within the clinic program, students:

- Work on open-ended, industry-relevant problems,
- Get the opportunities to engage with stakeholders from federal agencies and industries,
- Get the opportunity to collaborate in multidisciplinary teams,
- Engage with real data, physical constraints, and uncertainties to provide solutions to real-world problems,
- Apply systems design thinking concepts in modeling, experimentation, and design decisions.

These experiences, coupled with classroom concepts, provide a perspective that is essential for preparing students for contemporary industrial and research environments.

### 2.2.2 Engineering clinics layout

The engineering clinic primarily encompasses dynamic collaboration between student teams (graduate and undergraduate), faculty, and industry, creating a rich educational environment. The Chemical Engineering Department at Rowan University maintains a research-intensive culture and partnerships with diverse federal and industrial organizations. Notable collaborations are with the petrochemical industry, such as ExxonMobil and Valero Energy Corporation; pharmaceutical industry, such as Eli Lilly, AstraZeneca, Bristol Myers Squibb, and Pfizer; food and beverage industry, such as Nestle; specialty chemical industry, such as DuPont and PennAKem; and federal agencies, such as U.S. Environmental Protection Agency (EPA), U.S. Department of Energy, U.S. Army amongst others.

Within the first year, students are introduced to foundational engineering skills designed to develop analytical thinking and support reason-based learning. Building on this foundation, the second year emphasizes technical communication, with focused instruction on technical writing, data presentation, and oral communication—skills essential for effective documentation and professional practice. By the third and final year, students have accumulated sufficient theoretical knowledge and experiential learning to engage in discipline-specific and open-ended research projects. These projects are conducted under the joint supervision of graduate student mentors and faculty advisors, allowing students to integrate their prior coursework with applied research and design activities.

This curricular progression enables process design and modeling to be taught as integrated, system-level activities that reflect how engineering problems are addressed in professional and industrial settings. As students transition into upper-level clinics and research experiences, they are no longer positioned as passive recipients of problem statements but as active participants in defining, interpreting, and refining engineering challenges. Projects are initiated with an emphasis on understanding the overall system objectives, operational context, and performance criteria, often through direct engagement with industrial partners. These interactions expose students to realistic constraints, competing objectives, and evolving project requirements, reinforcing the necessity of system-level thinking from the outset.

In this environment, process design and modeling emerge as complementary tools for reasoning about complex systems rather than isolated technical deliverables. Students use models to formalize their understanding of a system, evaluate design alternatives, and anticipate system behavior under varying operating conditions. Design decisions are revisited iteratively as new experimental data, pilot-scale observations, and stakeholder feedback become available. This iterative refinement mirrors industrial design workflows, where models evolve alongside system understanding and are continuously validated against the physical behavior. Through sustained engagement in this end-to-end design process, students develop a holistic perspective of how process modeling informs design, optimization, and decision-making within complex engineered systems.

### 2.2.3 Student grading and assessment rubric

While the clinic framework defines how students engage with systems-oriented design problems, meaningful learning also depends on the performance evaluation of the students. To ensure alignment between instructional objectives and student outcomes, assessment strategies must reflect the iterative, integrative, and collaborative nature of clinical experiences. Accordingly, a structured grading rubric was developed to evaluate student performance across technical, analytical, and professional dimensions [7]. The rubric was informed by the work of Drs. Kevin Dahm, James, and Heidi Newell emphasize that effective assessment of complex engineering tasks requires clearly defined performance criteria, explicit achievement levels, and consistency across evaluators. Their framework highlights the importance of moving beyond purely outcome-based grading toward assessment approaches that capture students' reasoning, decision-making, and progression over time.

Consistent with this perspective, the rubric used in this study decomposes student performance into measurable categories aligned with the learning objectives of systems-oriented process design and modeling. These categories include problem formulation and system definition, appropriateness and justification of the modeling assumptions, integration of experimental data, quality of design decisions, and effectiveness of technical communication. Each category is evaluated using descriptive performance levels that articulate expectations for novice, developing, and proficient work. This structure enables evaluators to assess both the quality of the final deliverables and the rigor of the underlying design process, while also improving transparency for students and enhancing reliability in a team-based, open-ended learning environment.

## 3. CASE-STUDY OVERVIEW

Here, we present a case study grounded in Computer-Aided Process Engineering (CAPE), integrating process modeling, flowsheet synthesis, and systems-level design. Students develop and simulate flowsheets, scale-down industrial processes to pilot scale, and create CAD-based representations, with emphasis on instrumentation, control, and model-informed decision-making to bridge design and implementation. The scope of the project is to minimize oil downgrade during flushing operations in multiproduct petroleum pipelines. Batch transportation is mainly used in multiproduct oil pipelines, which refer to a network of interconnected pipelines for the continuous transport of several types of oil products in succession [8, 9]. The case study presented in this section explores the lubricant oil industry, which is a subsidiary of the petroleum industry. Unlike conventional pipeline systems, lubricant pipelines accommodate multiple oil grades with stricter quality tolerances and navigate intricate network layouts with bends, filters, and varied geometries, as illustrated in **Figure 1**.

One of the major operational challenges in multiproduct pipelines is product cross-contamination at the interface between oil product batches. The sequential transport of different petroleum products through the same pipeline results in a certain degree of mixing at the interface, leading to a mixture known as transmix or commingled oil. This transmix must be managed carefully to avoid contamination of the products, often requiring reprocessing, which increases operational costs.

A typical lubricant oil industry produces between 1, 500–2, 000 varied products annually. This production process is often segmented across distinct product lines, all converging into a single packaging line as illustrated in **Figure 1**, where residues from previous batches can accumulate and adhere to the walls of the pipelines. As highlighted previously, the issue of interfacial mixing becomes a problem where, due to the mode of transport, there is residue accumulation, impacting the quality of subsequent products. The residues not only compromise product quality and yield but also result in significant financial losses. To mitigate this, industries employ intermittent cleaning between product changeovers, known as flushing. Industries with aqueous or solid-based products usually rinse pipelines with water or inert gas, followed by drying before the next cycle. Unfortunately, oil-based systems found in lubricant manufacturing and blending pose a unique challenge because aqueous media cannot be used for cleaning [10].

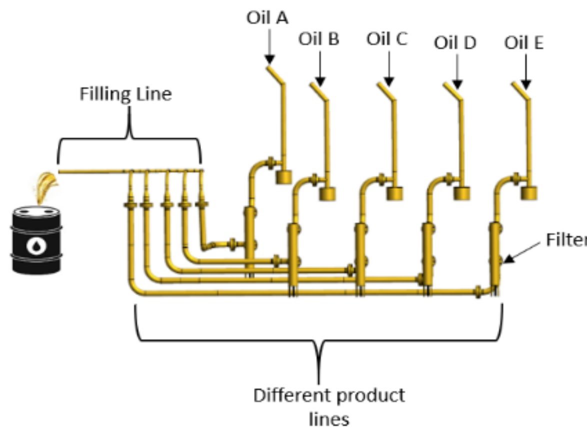


**Figure 1**. Schematic of a multiproduct pipeline with several products connected to a common filling line for lubricant oil packaging.

The products produced are often destined for sensitive applications, such as in automotive engines and turbines, where even small amounts of contamination would impair performance. Hence, pipeline flushing is a frequently scheduled operation to avoid contamination and mixing of consecutive product batches. The lubricant oil industry usually employs a product changeover operation that involves two stages: (i) removal of the previous (residual) oils from straight sections via the pipeline inspection gauges (PIGs), which is 97% efficient in residual displacement, and (ii) oil removal from the sections with varying diameters, auxiliary equipment, bends, and turns, often known as the unpiggable sections. Stage (ii) is usually accomplished by passing the new oil through the unpiggable section until the residual oil is displaced from the pipeline [9, 11]. This process inevitably leads to the formation of mixed oil segments, which are of limited economic value and must be carefully managed.

At present, flushing operations in lubricant pipelines remain empirical, relying on operators' experience and trial-and-error approaches to determine flush times and volumes. Even at this, industrial practices themselves differ significantly; each facility adopts unique operational procedures, flush volumes, and sequencing protocols based on experience rather than predictive understanding. This lack of standardization across operators results in inconsistent outcomes, and suboptimal use of resources. This lack of predictive capability results in long hold times, downgrading of high-value products, and substantial capital losses. The operational inefficiency of current practices, combined with the complexity of lubricant pipeline networks, highlights the need for environmentally friendly, cost-effective, and energy-efficient solutions to optimize flushing operations.

Having established the industrial context and technical scope of the case study, the following section describes how the project was intentionally structured to guide students through the core stages of process design and modeling using a systems design thinking approach.

# 4. SOLUTION DEVELOPMENT

## 4.1 Experiential learning: engagement with stakeholders and design objectives

Following an initial preview of the industrial challenge, students were guided to move beyond a qualitative problem statement toward the formulation of explicit engineering objectives using a systems design thinking approach. Upon visits to the plant and engagement with stakeholders, students identified persistent inefficiencies during product changeovers in multiproduct pipelines, where flushing operations relied heavily on trial-and-error practices, leading to excessive use of resources, oil for flushing, extended downtime, large volumes of mixed oil formation, and inconsistent product quality. From this context, students were tasked with translating the operational inefficiencies into quantifiable and actionable engineering goals. Two primary objectives emerged: (i) the development of a standardized, repeatable flushing protocol applicable across a range of operating conditions, and (ii) the replacement of heuristic decision-making with a model-based framework capable of supporting smart, data-driven operations.

To achieve these objectives, students engaged in structured and iterative interactions with multiple stakeholders, including plant operators, process engineers, and technical managers. These engagements were conducted through scheduled meetings, progress reviews, and informal technical discussions, providing students with firsthand exposure to professional communication in an industrial setting. Through this process, students learned to elicit requirements, negotiate technical expectations, and reconcile conflicting constraints, which are key competencies in requirements engineering. Importantly, students quickly recognized that any proposed solution would need to be economically viable and minimally disruptive to existing operations, reinforcing the necessity of designing under real-world constraints rather than idealized assumptions. As part of the experiential learning process, students explored alternative approaches to conventional flushing strategies and evaluated their feasibility relative to cost, scalability, and operational complexity. Some of the potential flushing alternatives explored included pipeline coating [12], fluid blasting [13], gel pigging [14], amongst others. These explorations revealed significant limitations associated with intrusive process modifications, prompting a shift toward low-cost, adaptable solutions. This realization ultimately motivated the decision to replicate industrial operations at pilot scale, enabling controlled experimentation while preserving fidelity to real plant behavior. Through this phase, students internalized systems design principles by learning to balance technical ambition with economic and operational realities.

## 4.2 Pilot plant architecture: design constraints, equipment, and validation approach

A central element of the project involved the design and construction of a pilot plant capable of mirroring the dynamics of the industrial flushing operation. Students were introduced to a fundamental question in process design: how do we design a system mimicking the industrial operation? [15] and tasked with translating conceptual objectives into a physical system. This required decisions regarding equipment selection, piping configuration, sensor placement, control architecture, and data acquisition systems, all of which were informed by both classroom theory and industrial input.

The pilot plant was intentionally designed to serve as both a physical testbed and the foundation of a cyber-physical system. Students evaluated which unit operations and components were essential to replicate industrial behavior, and which could be simplified without compromising system integrity. Key considerations included flow regimes, viscosity contrasts between fluids, the right choice of pump considering the nature of lubricant oils, and the impact of pipeline geometry on mixing behavior. Scaling down from industrial to pilot scale required students to apply principles of similitude and dimensional analysis, assessing the effects of flow rates, pipe geometries, and fluid properties on fluid transport and the ability to replicate the larger system. Product purity determination is done through viscosity testing, as it reflects the functional performance of the lubricant oil product. For instance, if the oil viscosity deviates from specification, it may fail to reduce friction, prevent wear, and dissipate heat.

At industry, this is tested through sampling at the end of each flush operation. As part of the equipment installed on the pilot plant, students installed an in-line viscometer for continuous viscosity measurement during the flushing. The interactions of all equipment installed

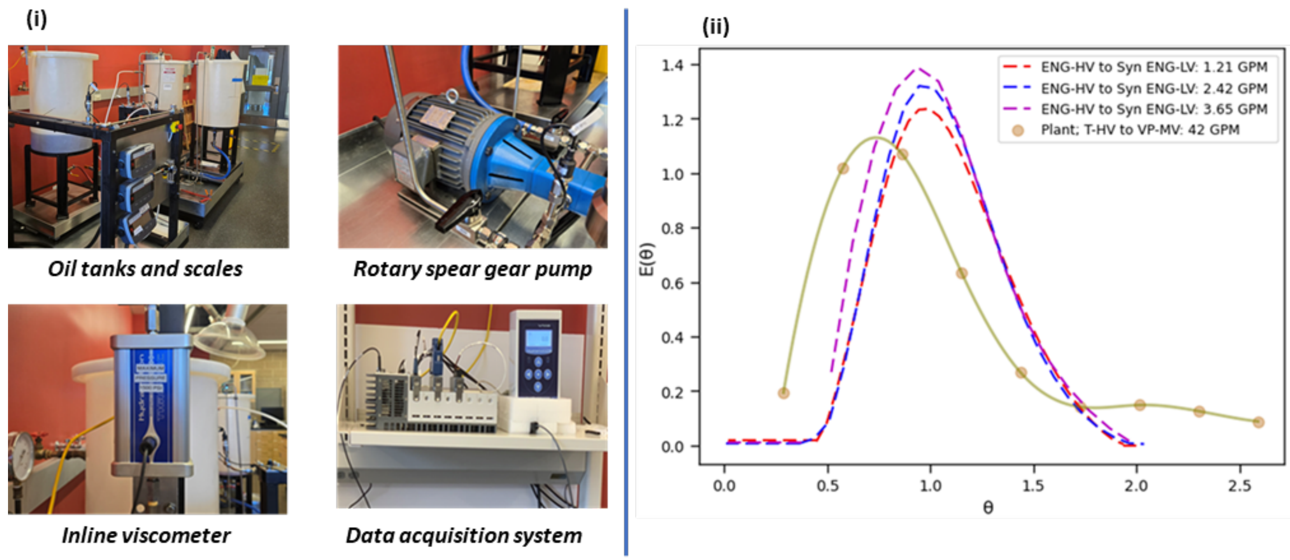


**Figure 2**. Developed 1/5th industrial-scale pilot plant illustrating (i) the equipment installed in the pilot plant (oil tanks, scales-for mass balance; rotary spear gear pump-for pumping the high viscous lubricant oils; inline viscometer-for real-time viscosity measurement; and data acquisition system-for seamless integration of all measurements and data collection) and (ii) the validation between pilot and industrial plant through residence time distribution studies-a plot of dimensionless RTD, E(ϴ) against dimensionless time, ϴ.

are through a data acquisition system, which integrates all these components in LabVIEW programming to collect data across multiple channels. Simultaneously, students are introduced to the fundamentals of process instrumentation and data acquisition framework, selecting sensors capable of capturing relevant process variables such as pump power, pressure, viscosity, temperature, and change in mass. Emphasis was placed on understanding how different signals are generated, interpreted, and integrated to produce actionable insight.

To validate the fidelity of the pilot plant, students conducted residence time distribution (RTD) studies comparing experimental results against theoretical expectations and industrial data. These experiments provided a concrete mechanism for students to assess whether the scaled system accurately reflected industrial dynamics [9, 16]. This phase of the project tightly coupled classroom concepts, transport phenomena, process dynamics, and control, with hands-on engineering design. By building a physical system that directly informed modeling efforts, students experienced the full lifecycle of process design, from abstraction to implementation. This is depicted in **Figure 2**. The pilot plant thus became a critical educational bridge, reinforcing systems thinking while anchoring modeling activities in observable, real-world behavior.

## 4.3 Modeling strategy: systems-level decision support tool

With experimental infrastructure in place, students transitioned to the development of process models intended to capture the flushing dynamics observed in the pilot plant. Rather than prescribing a single modeling approach, students were guided to evaluate alternative strategies, including mechanistic, data-driven, and hybrid models. This evaluation required students to reflect on the purpose of the model prediction, optimization, or decision support and to select an approach consistent with available data, computational complexity, and interpretability. A critical aspect of the process modeling is what is referred to as "*know-how*" for processes. Thus, students were exposed to the theories of process dynamics: how a process changes over time; process identification: building a model from process data; and process control: what are the parameters of interest to keep the process at desired conditions, all of which are key in understanding and developing a model for the flushing process. Emphasis was placed on ensuring that the model assumptions were clear and consistent. Students were encouraged to justify assumptions related to flow behavior, mixing efficiency, and parameter estimation, and to assess the impact of these assumptions on the model accuracy. Parameter identification was performed using experimental data obtained from the pilot plant, reinforcing the iterative relationship between modeling and experimentation. Through this process, students learned that models are not static representations, but evolving tools that must be continually refined as new data becomes available.

From an instructional standpoint, modeling was framed as a decision-making tool rather than an abstract mathematical exercise. Students evaluated model limitations, explored sensitivity to key parameters, and assessed the trade-off between model fidelity and usability. This approach helped students develop an appreciation for “fit-for-purpose” modeling, where the goal is not maximum complexity, but actionable insight. Results from the developed models on some test case flushing experiments are depicted in **Figure 3**.

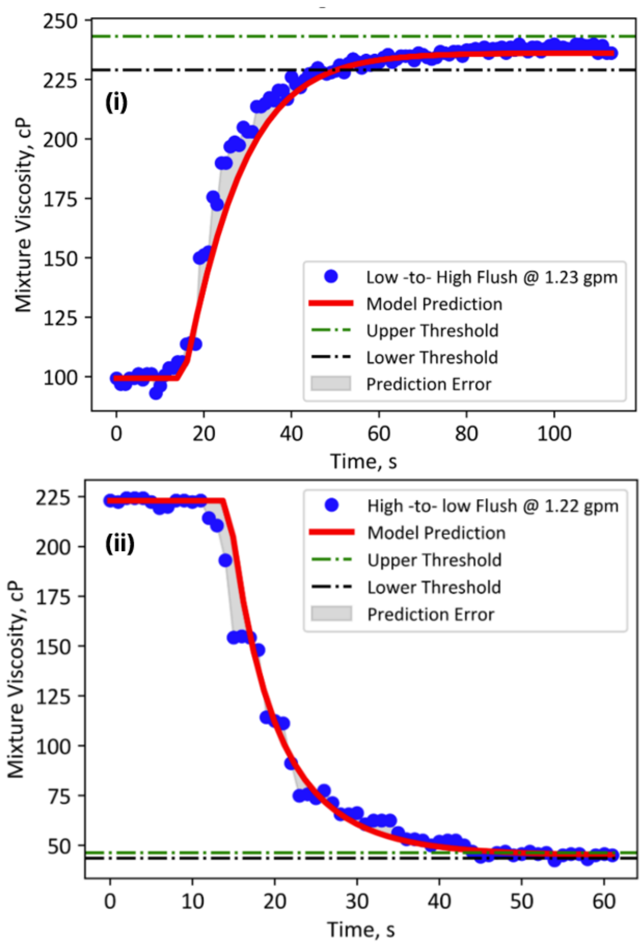


**Figure 3.** Sample model results validated against experimental flush data performed on the pilot plant for (i) a change from a low viscosity oil to a high viscosity oil and (ii) a change from a high viscosity oil to a low viscosity oil.

The final stage of the project focused on translating validated models into decision support tools capable of informing operational strategy. Students employed their models to evaluate economic, temporal, and performance-based metrics associated with different flushing scenarios. These analyses included minimizing flushing time, enhancing the effective use of oil during flushing, and identifying operating conditions that balance efficiency with robustness.

Optimization was introduced as an extension of design thinking rather than a purely mathematical construct. Students explored trade-offs between competing objectives and learned to interpret optimization results within the broader system context. This systems-level perspective reinforced the idea that optimal solutions are contingent on constraints, uncertainty, and stakeholder priorities.

Through this stage, students completed the full cycle of process design and modeling from problem formulation to decision support, demonstrating how systems design thinking can be effectively embedded within undergraduate education. The case study thus served not only as a technical challenge but as a structured learning environment in which students developed professional competencies essential for modern process engineers.

## 5. STUDENT LEARNING OUTCOMES AND CONCLUSION

This case study demonstrates how a research-integrated clinic framework can be intentionally structured to teach process design and modeling as interconnected, systems-oriented competencies rather than isolated technical skills. By exposing students to critical industrial challenges, the project enabled students to experience the full engineering design lifecycle from problem definition and stakeholder engagement to modeling, experimentation, and decision support. Rather than receiving predefined objectives or idealized datasets, students were required to translate ambiguous operational challenges into structured engineering goals, reinforcing the central role of problem formulation in professional practice. From a learning perspective, the project fostered student development across multiple dimensions. Early engagement with industrial stakeholders strengthened professional communication skills and exposed students to requirements engineering under real-world constraints. Students learned to negotiate technical feasibility, economic limitations, and operational practicality while maintaining alignment with overarching system objectives. These experiences directly supported the development of systems thinking, as students were required to consider how design choices influenced overall process performance.

The design and validation of the pilot plant played a critical role in bridging theory and practice. Through scaling analysis, equipment selection, and residence time distribution studies, students applied foundational concepts from transport phenomena and process dynamics in a real-world setting. The developed pilot plant reinforced the importance of experimental and model validation, exposing students to the limitations of purely theoretical models. Also, students gained experience in data acquisition systems and interpreting real process signals, skills that are increasingly essential in modern, data-rich industrial environments. Modeling activities further deepened student understanding by reframing models as decision-support tools rather than purely predictive constructs. By comparing mechanistic, data-driven, and hybrid approaches, students developed an appreciation for model selection, assumption transparency, and parameter identification. Sensitivity analysis and model validation exercises helped students recognize the trade-offs between fidelity, interpretability, and usability, ensuring critical judgment in model-based decision-making.

Overall, the case study illustrates how process design and modeling can be taught holistically through experiential, industry-engaged learning. Students completing the project demonstrated measurable gains in systems thinking, professional communication, experimental design, and model-based reasoning. More importantly, they developed a mindset aligned with contemporary engineering practice, one that values integration, iteration, and informed decision-making under uncertainty. These outcomes and exposure ensured that students are prepared for the multifaceted challenges of modern process engineering, while the clinic framework provides a replicable model for experiential learning at other institutions.

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