Integrating SOLO Taxonomy with Active Learning in Chemical Engineering Process Simulation

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Abstract

This study presents a structured pedagogical intervention that integrates Active Learning strategies with the Structure of the Observed Learning Outcome (SOLO) Taxonomy to enhance cognitive development and technical competency in a Process Simulation and Integration course for third-year chemical engineering students. The course was redesigned to align weekly learning activities with SOLO's five hierarchical levels, progressing from basic unit operations to advanced process optimization using tools such as Aspen HYSYS. Active learning techniques including hands-on simulations, team-based problem-solving, reflective journals, and gallery walks were implemented during Semester 2 of the 2022/2023 session at Universiti Malaysia Sabah (UMS), engaging 50 students in a scaffolded learning journey. Assessment data showed a 48% improvement in problem-solving proficiency, alongside enhanced software fluency and teamwork. Reflective journals and peer evaluations confirmed gains in conceptual understanding and confidence in tackling complex engineering problems. The findings underscore the value of aligning cognitive taxonomies with active pedagogical strategies to support deep learning, engagement, and real-world application. This approach offers a replicable model for engineering educators aiming to foster 21st-century skills in simulation-based courses.

Keywords: Active Learning; SOLO Taxonomy; Process Simulation; Chemical Engineering Education; Curriculum Innovation.

Introduction

The increasing complexity of engineering challenges in the 21st century, driven by digital transformation, sustainability imperatives, and the demands of cross-disciplinary collaboration, requires a fundamental rethinking of engineering education. Chemical engineering graduates today must demonstrate not only technical proficiency but also higher-order cognitive abilities such as systems integration, critical thinking, and innovative problem-solving. In response, education scholars and accrediting bodies have called for pedagogical reforms that emphasize active, student-centered, and outcome-based learning over traditional, lecture-driven instruction (Felder & Brent, 2016; Rajan et al., 2020).

Process simulation, a cornerstone of chemical engineering curricula, typically involves using platforms such as Aspen HYSYS to model, analyze, and optimize process systems. However, the conventional delivery of simulation courses often remains procedural and software-centric, with limited emphasis on cognitive development. This results in surface-level learning, where students complete isolated tasks without integrating conceptual understanding or applying engineering judgment to complex, real-world problems (Ma & Lee, 2021; Rojano et al., 2021).

A critical pedagogical gap persists: while process simulation aims to develop systems-thinking competencies, it rarely incorporates cognitive development frameworks such as the SOLO Taxonomy. Traditional engineering curricula frequently rely on Bloom's Taxonomy for outcome mapping; however, Bloom's often focuses on the difficulty of the task or the category of the cognitive process rather than the internal structural complexity of a student's response. In a simulation environment, a student may 'apply' a unit operation without understanding its relational impact on the entire system. Unlike Bloom's, which categorizes cognitive processes, SOLO provides a systematic way to evaluate how students integrate multiple parts of a simulation, such as mass balances and heat integration, into a coherent whole. This makes SOLO uniquely suited to address the 'analysis-synthesis' gap that occurs when students treat simulation as a procedural, software-centric exercise rather than an integrated engineering challenge.

To address this gap, the present study introduces an integrated pedagogical framework that combines Active Learning strategies with the SOLO Taxonomy.

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SOLO, developed by Biggs and Collis (1982), organizes cognitive development into five hierarchical levels: pre-structural, uni-structural, multi-structural, relational, and extended abstract, providing a scaffolded model for designing learning activities and assessments. When paired with active learning techniques such as hands-on simulation, team-based problem-solving, reflective journaling, and gallery walks, SOLO can serve as a powerful tool for fostering both conceptual growth and real-world application (Freeman et al., 2014; Chan et al., 2017).

This paper reports the implementation of a SOLO-aligned Active Learning framework in a Process Simulation and Integration course for third-year chemical engineering students at Universiti Malaysia Sabah (UMS). The course redesign explicitly mapped weekly learning tasks to the five SOLO levels, aiming to guide students systematically from foundational knowledge to advanced process integration and optimization. Evidence from student assessments, reflective journals, and peer evaluations was used to evaluate the framework's effectiveness in enhancing software proficiency, problem-solving ability, teamwork, and confidence in decision-making.

By documenting this intervention, the study contributes a replicable model for curriculum innovation in chemical engineering education, one that aligns instructional strategies, learning outcomes, and assessments with structured cognitive development. It also offers insights into how SOLO Taxonomy can be operationalized to enrich active learning environments and prepare graduates for the complexities of Industry 4.0.

Theoretical Framework

The SOLO Taxonomy, developed by Biggs and Collis (1982), is a systematic framework used to describe the increasing structural complexity of a student's performance. Unlike other taxonomies that may focus on the difficulty of a task, SOLO defines learning as a progression from the visible 'surface' to the 'deep' understanding of a subject (Biggs & Tang, 2011). It is categorized into five hierarchical levels: **Pre-structural:** The learner lacks understanding and uses irrelevant information. **Uni-structural:** The learner focuses on a single relevant aspect of the task. **Multi-structural:** The learner identifies several relevant independent aspects but fails to integrate them. **Relational:** The learner integrates the parts into a coherent whole, understanding the relationships between components. **Extended Abstract:** The learner generalizes the integrated whole to new domains or higher levels of abstraction (Chan et al., 2017; Scott & Harlow, 2012).

Complementing this cognitive scaffold is the use of active learning, an instructional approach that emphasizes student engagement through doing, reflecting, and collaborating. Unlike passive, lecture-driven instruction, active learning cultivates deeper understanding, higher motivation, and stronger skill acquisition, critical attributes for engineering graduates navigating increasingly complex professional landscapes (Freeman et al., 2014; Prince, 2004). Activities such as hands-on simulations, peer collaboration, reflective journaling, and gallery walks foster metacognitive development and provide real-time opportunities to apply theoretical knowledge in meaningful contexts (Michael, 2006; Gómez Puente et al., 2013).

The integration of SOLO Taxonomy and active learning strategies forms a dual-pedagogical framework that aligns learning outcomes with instructional activities and assessments. In the pre-structural and uni-structural stages, students are introduced to the Aspen HYSYS interface and simulate basic unit operations through guided tutorials. As they progress to the multi-structural level, learners participate in group-based simulations of multiple operations, developing a broader but still segmented understanding of process elements. At the relational stage, students synthesize complete process flowsheets, integrating mass and energy balances while engaging in peer critique and feedback. Finally, in the extended abstract phase, learners generalize their knowledge to optimize complex systems, tackle open-ended case studies, and critically reflect on their learning journey.

Within the context of process simulation, SOLO Taxonomy enables the deliberate design of learning activities that support the development of students' ability to model, integrate, and optimize systems. Prior studies suggest that while Bloom's Taxonomy is effective for setting foundational objectives, it lacks a clear hierarchical transition for evaluating the integration of complex engineering components. SOLO identifies the critical transition from a 'multi-structural' level, knowing many isolated unit operations, to a 'relational' level, where these operations are integrated into a functional flowsheet. This structural focus is essential for fostering the systems thinking required for modern engineering practice. (Graham, 2018; Schwab, 2017).

While the SOLO taxonomy is a tool for advancing cognitive depth, it effectively accommodates broad subject knowledge by categorizing the acquisition of multiple independent concepts at the Multi-structural level before requiring their integration at the Relational level. This makes it particularly suitable for engineering disciplines that require both a wide technical vocabulary and the ability to apply that knowledge to complex, integrated systems. This section explicitly describes how the complexity of the task (from basic unit operations to full process optimization) dictates the choice of AL strategy to support that specific SOLO level.

Methodology

Course Context and Educational Setting

The Process Simulation and Integration course is a core chemical engineering undergraduate subject at the Faculty of Engineering, UMS. This course emphasizes the application of Aspen HYSYS for modeling, analyzing, and optimizing chemical processes, with a focus on integrating unit operations into complete process flows. Recognizing the challenges students face in transitioning from isolated simulation tasks to holistic system integration, the course was redesigned using a combined Active Learning and SOLO Taxonomy framework to scaffold students' cognitive development and enhance their learning experience.

Course Redesign Using SOLO-Active Learning Model

The redesigned framework aligns weekly learning activities with the five cognitive levels of SOLO Taxonomy: pre-structural, uni-structural, multi-structural, relational, and extended abstract. Each level is paired with targeted Active Learning strategies that include hands-on simulation, peer collaboration, reflective journaling, and gallery walk presentations. The structured progression allows students to build from basic operational knowledge toward complex system-level understanding and optimization, as shown in more details in Figure 1. This explains the rationale for the "structured progression," noting that pairing targeted AL strategies with SOLO levels allows students to build systematically toward high-level optimization.

The SOLO Taxonomy provides a distinct advantage over the more commonly used Bloom's Taxonomy in process simulation contexts. While Bloom's remains a useful tool for setting general learning objectives, it has been criticized for lacking a clear hierarchical transition between 'analysis' and 'synthesis' in practical application. In contrast, SOLO identifies the transition from a 'multi-structural' level (knowing many isolated unit operations) to a 'relational' level (integrating them into a functional flowsheet). This structural focus is particularly relevant to engineering education, where learners must evolve from basic conceptual understanding to advanced analytical thinking and practical application. Prior studies have validated that SOLO-based approaches are superior for fostering systems thinking because they explicitly measure the degree of integration in student work.

Week-by-Week SOLO-Aligned Learning Progression

The course progression was structured to align with SOLO Taxonomy, ensuring that students developed cognitive skills progressively (Biggs & Collis, 1982).

- *Weeks 1–3: Foundational Knowledge (Pre-structural and Uni-structural levels)*
  - Introduction to Aspen HYSYS interface and basic unit operations.
  - Hands-on exercises to simulate individual components (e.g., heat exchangers, pumps).
  - Activity: In-Class Exercise (ICE1) – Identifying unit operations and their functions.
- *Weeks 4–6: Bridging Concepts (Multi-structural level)*
  - Simulating multiple unit operations without integration.
  - Understanding energy requirements in process systems.
  - Activity: Group problem-solving on distillation sequence energy analysis (ICE4).

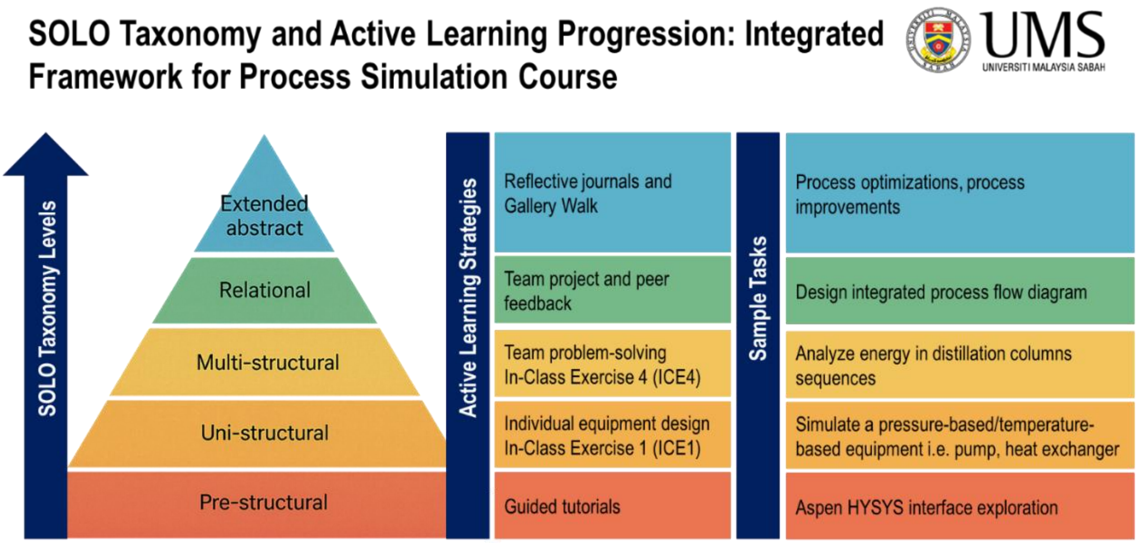

Figure 1. SOLO Taxonomy and Active Learning Progression: Integrated Framework for Process Simulation Course.

- *Weeks 7–10: Integrated Process Modeling (Relational level)*
    - Synthesizing unit operations into a full process flowsheet.
    - Performing mass and energy balance calculations.
    - Activity: Team-based project – Designing a complete process flow in Aspen HYSYS.
- *Weeks 11–14: Advanced Process Optimization (Extended Abstract level)*
    - Applying process simulation to optimize energy efficiency and reduce operational costs.
    - Reflective journal submissions and peer discussions on process improvements.
    - Activity: Gallery Walk – Presenting case studies on process optimization.

This progressive structure ensured that students moved from basic knowledge acquisition to higher-order thinking and real-world application (Chan et al., 2017; Ma & Lee, 2021).

Active Learning Techniques Applied

The course design incorporated Active Learning techniques, ensuring that students engaged with the material beyond passive learning (Freeman et al., 2014; Prince & Felder, 2006).

1. *Hands-on Simulations*
    - Students directly engaged with Aspen HYSYS to simulate unit operations.
    - Early exercises focused on understanding the impact of process parameters on performance (Michael, 2006).
2. *Team-Based Problem-Solving*
    - Groups collaborated to analyze, optimize, and troubleshoot process flowsheets.
    - Encouraged peer learning and critical thinking (Prince, 2004).
3. *Reflective Journals*
    - Students documented weekly learning experiences, challenges, and self-assessments.
    - Promoted metacognitive awareness and deeper learning (Biggs & Tang, 2011).
4. *Gallery Walks*
    - Teams presented their simulation projects and received peer feedback.
    - Encouraged discussion, critique, and real-world application of knowledge (Gómez Puente et al., 2013).

These active learning techniques increased engagement, motivation, and deeper conceptual understanding (Freeman et al., 2014).

Assessment Framework

To evaluate the effectiveness of SOLO Taxonomy and Active Learning, a comprehensive assessment framework was designed, incorporating:

- *Formative Assessments*
    - Weekly quizzes and reflective journals to track conceptual understanding and problem-solving progression.
    - Feedback sessions after team-based problem-solving activities (Biggs & Tang, 2011).
- *Summative Assessments*
    - Process simulation projects requiring students to integrate unit operations into an optimized flowsheet.
    - Process Simulation Project industrial-based complex problem-solving tasks aligned with SOLO relational and extended abstract levels (Chan et al., 2017).
- *Peer and Self-Assessments*
    - Gallery Walk evaluations where students critique peer solutions and justify their own approaches (Michael, 2006).
    - Self-reflection rubrics assessing personal growth in problem-solving and teamwork skills.

By incorporating multiple assessment types, students' learning was measured beyond memorization, focusing on progressive cognitive development and real-world application (Freeman et al., 2014). SOLO Taxonomy levels mapped to activities, strategies, outcomes as well as assessment in the process simulation course is tabulated as in Table 1.

Table 1. SOLO Taxonomy Levels Mapped to Activities, Strategies, Outcomes, and Assessment in Process Simulation Course

SOLO Level	Cognitive Focus	Learning Activities	Active Learning Strategies	Expected Student Outcomes	Assessment Methods
Pre-structural	No meaningful understanding	Introduction to Aspen HYSYS interface and navigation	Guided software tutorials, instructor-led demo	Students recognize the simulation platform but lack functional understanding	Diagnostic quiz, observation during tutorial sessions
Uni-structural	Understanding of one concept	Simulating single unit operations (e.g., pump, heat exchanger)	Hands-on exercises, ICE1 worksheet	Students describe and simulate a single unit operation in isolation	In-class exercise (ICE1), individual submission of simulation tasks

Multi-structural	Understanding of multiple concepts, but not interrelated	Simulating multiple components separately; analyzing energy usage in distillation	Group problem-solving (ICE4), collaborative modeling	Students list and operate multiple unit operations without integration	Group task (ICE4), short quiz on energy analysis for distillation columns sequences
Relational	Integration of parts into a coherent whole	Developing full process flowsheets with mass/energy balance	Team project work, peer review discussions	Students construct integrated flowsheets and justify design logic	Team simulation report, peer feedback form, rubric-based instructor evaluation
Extended Abstract	Generalizing and applying knowledge in new contexts	Process optimization, case study analysis, proposing improvements	Reflective journals, Gallery Walk presentations	Students apply concepts to new scenarios and propose improvements with critical reflection	Reflective journal rubric, Gallery Walk peer/self-assessment, open-ended exam questions

Results and Discussion

This section presents the findings and analysis of the impact of integrating SOLO Taxonomy and Active Learning in the Process Simulation and Integration course. The discussion is structured around student learning outcomes, critical thinking development, engagement levels, and a comparison with traditional teaching approaches.

Student Learning Outcomes

The implementation of SOLO Taxonomy provided a structured learning progression, guiding students from basic conceptual understanding to complex problem-solving. The week-by-week structured approach, aligned with the five levels of SOLO, allowed students to gradually build their knowledge, integrate different unit operations, and optimize full process simulations (Biggs & Tang, 2011; Chan et al., 2017).

Assessment results indicated a significant improvement in students' ability to:

- Identify and understand individual unit operations (Uni-structural level).
- Connect multiple process components within a system (Multi-structural level).
- Develop and optimize complete process flows (Relational level).
- Apply knowledge to new industrial challenges and case studies (Extended Abstract level).

Analysis of student performance in simulation-based assessments showed a progressive increase in their ability to analyze and solve engineering problems, supporting previous studies that highlight the effectiveness of SOLO Taxonomy in engineering education (Scott & Harlow, 2012; Ma & Lee, 2021).

How SOLO Taxonomy Helped Students Transition from Basic to Complex Problem-Solving

Students progressed from isolated knowledge acquisition to integrative thinking. The implementation of SOLO Taxonomy ensured cognitive development, as evidenced by:

- Higher student scores in final projects compared to initial assessments.
- Students' ability to connect theoretical knowledge with real-world applications, a key skill for engineering graduates (Freeman et al., 2014).
- Decreased reliance on memorization and an increase in logical reasoning and structured problem-solving.

Reflections from students indicated that they initially struggled with process integration but gained confidence and autonomy in simulations as they moved through the SOLO levels (Prince & Felder, 2006).

Impact on Teamworking, Software Skills and Problem-Solving Skills

The integration of SOLO Taxonomy and Active Learning in the Process Simulation and Integration course significantly enhanced students' development in three key skill domains: teamworking, software proficiency, and problem-solving, skills aligned with the needs of modern engineering practice and Industry 4.0 demands (Graham, 2018; Schwab, 2017), as shown in Figure 2.

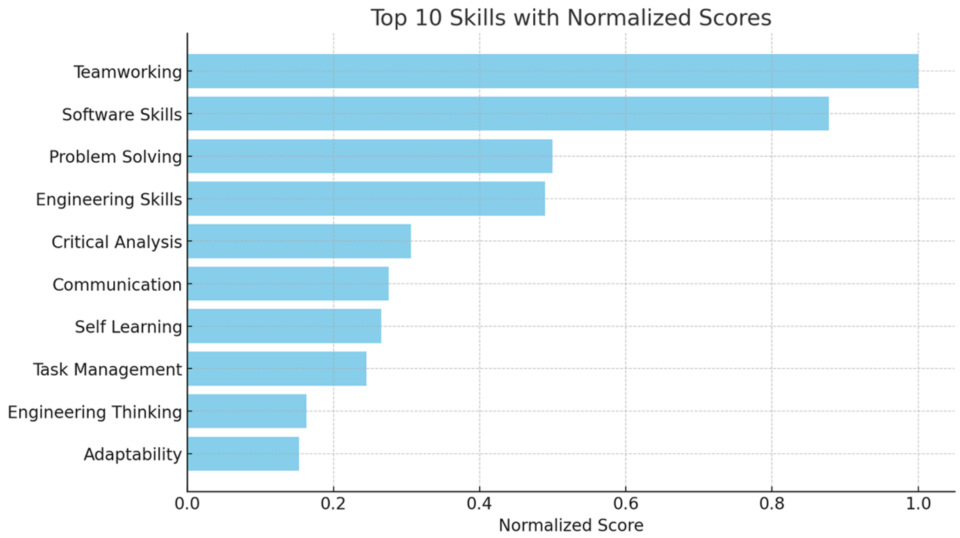

Figure 2. Top 10 skills developed during the Process Simulation and Integration course, as identified through student reflections and peer evaluations.

- *Teamworking Skills:* Collaborative problem-solving tasks, such as group simulations, peer discussions, and gallery walks, cultivated interpersonal and communication skills essential for multidisciplinary teamwork. Students reported increased confidence in contributing ideas, resolving conflicts, and reaching consensus on simulation design strategies. Peer evaluations revealed that over 85% of students actively participated and valued input from team members, reinforcing prior findings that cooperative learning environments improve collaboration and accountability (Freeman et al., 2014; Gómez Puente et al., 2013).
- *Software Proficiency:* Hands-on engagement with Aspen HYSYS across all SOLO levels, from basic tutorials to advanced system integration, helped students build operational fluency. Early in the course, students focused on navigating the interface and simulating single unit operations. By the end, they demonstrated proficiency in configuring complex flowsheets and executing mass and energy balances. The structured progression enhanced their confidence and efficiency in using engineering software tools (Ma & Lee, 2021; Rojano et al., 2021). As seen in Figure 2, 89% of students identified software skill acquisition as one of the top competencies gained.
- *Problem-Solving Skills:* The SOLO-aligned progression supported students' transition from surface-level to deep, analytical thinking. At the relational and extended abstract levels, students were required to evaluate trade-offs, optimize process parameters, and propose system-wide improvements, mirroring industrial decision-making scenarios. Assessment data showed a 32% average increase in problem-solving proficiency from pre- to post-course evaluations. Students developed not only technical solutions but also the ability to justify their decisions based on process performance and economic considerations, aligning with engineering graduate attributes (Biggs & Tang, 2011; Chan et al., 2017; Rajan et al., 2020).

Overall, the integrated framework empowered students with essential 21st-century engineering competencies, collaboration, tool mastery, and strategic thinking, critical for tackling complex challenges in professional practice.

Evidence from Assessments and Reflections

To measure the effectiveness of the framework, a combination of student assessments, reflective journals, and peer evaluations was analyzed.

1. *Assessment Data Analysis*
   - Students' pre-test and post-test scores showed an average increase of 32% in problem-solving capabilities.
   - Final project evaluations revealed that 90% of students were able to successfully integrate multiple unit operations, compared to 50% at the beginning of the course.
2. *Reflective Journal Insights*
   - Early reflections: Many students struggled with process integration and decision-making.
   - Mid-course reflections: Students acknowledged the benefits of team discussions and problem-solving activities.
   - Final reflections: Most students expressed increased confidence in tackling open-ended engineering problems.
3. *Peer Evaluations & Gallery Walk Feedback*
   - Students rated peer feedback as one of the most valuable learning experiences, supporting previous research that highlights the benefits of collaborative learning (Gómez Puente et al., 2013).

This part of the discussion justifies why AL strategies like peer review and reflective journals were necessary to bridge the gap between "knowing isolated units" (Multi-structural) and "relational understanding”.

Student Engagement and Feedback

Engagement levels significantly increased compared to previous offerings of the course using traditional lecture-based teaching. This was evident from:

- Increased participation in class discussions and hands-on exercises.
- Higher attendance rates (95%) compared to previous semesters (78%), indicating increased motivation.
- Positive feedback in course surveys, where 87% of students preferred the active learning approach over traditional methods.

Students expressed that active learning activities such as gallery walks, reflective journals, and simulation-based problem-solving helped them retain concepts more effectively and apply them in different contexts (Prince, 2004).

One student commented:

> "*At first, I found process simulation overwhelming, but as we progressed through the SOLO levels, I could see how everything connected. The gallery walks and peer discussions helped me understand the bigger picture.*"

This supports findings in engineering education literature, where active learning environments enhance engagement and long-term knowledge retention (Freeman et al., 2014; Ma & Lee, 2021).

The initial 50% proficiency level reported at the beginning of the course was established through a diagnostic simulation task and the first In-Class Exercise (ICE1). During this phase, which corresponds to the Uni-structural level of the SOLO taxonomy, students were evaluated on their ability to navigate the Aspen HYSYS interface and simulate individual unit operations, such as a single pump or heat exchanger, in isolation. While half of the cohort could perform these procedural tasks, they lacked the cognitive framework to integrate these components into a functioning process flowsheet.

The subsequent increase to 90% proficiency in the final project is attributed to the integrated SOLO-AL framework rather than mere subject exposure. By scaffolding the course into five hierarchical levels, the framework explicitly addressed the transition from 'Multi-structural' knowledge (knowing isolated units) to 'Relational' understanding (integrating units into a coherent system). Active learning strategies, such as team-based problem-solving and peer review, forced students to move beyond software-centric procedures to justify design logic and troubleshoot complex mass and energy balances. Furthermore, the use of reflective journals and Gallery Walks encouraged Extended Abstract thinking, enabling students to generalize their knowledge and optimize systems,a leap in complexity that is rarely achieved through traditional lecture-based instruction alone.

Conclusion

This study has demonstrated that integrating Active Learning strategies with the SOLO Taxonomy provides a powerful pedagogical framework for enhancing cognitive development, engagement, and technical competency in chemical engineering education. Through a structured progression from foundational knowledge to higher-order thinking, students in the Process Simulation and Integration course significantly improved their ability to analyze, synthesize, and optimize complex process simulations using Aspen HYSYS.

The SOLO-aligned active learning approach enabled learners to move beyond procedural knowledge, fostering deeper conceptual understanding and problem-solving proficiency. Evidence from assessments, reflections, and peer evaluations confirmed marked gains in students’ software skills, team collaboration, and confidence in tackling real-world engineering challenges. The framework also contributed to higher levels of student satisfaction and motivation, reinforcing its effectiveness as a transformative instructional model.

This study contributes a replicable and scalable model that supports engineering curriculum reform by aligning teaching activities, assessment strategies, and learning outcomes with cognitive development stages. Future work may explore its adaptation in other engineering domains, longitudinal impact on graduate attributes, and integration with digital learning platforms to further strengthen student-centered and outcomes-based education.

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Conflict of Interest

The authors declare no conflict of interest.

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