BEYOND LINEAR CDIO: PROCESS PATTERNS IN RENOVATION-ORIENTED ARCHITECTURAL ENGINEERING EDUCATION

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ABSTRACT

Architectural engineering education can adopt the Conceive-Design-Implement-Operate (CDIO) framework as a linear representation of design–engineering processes. However, renovation projects are inherently iterative and constraint-driven, challenging linear interpretations of CDIO. While iteration is acknowledged conceptually within the CDIO literature, empirical studies that make such process patterns visible in educational practice, particularly in renovation-oriented architectural engineering, remain limited. This paper addresses this gap by examining how CDIO is enacted in practice within a renovation-focused architectural engineering studio through a combined analysis of task-level process data and experiential indicators. Empirical material consists of task-sequence data from 19 students, yielding 207 CDIO-aligned transitions derived from course submissions, together with 226 task-based survey records capturing perceived Purpose, Control, Effort, Persistence, Enjoyment, and Groupmate contribution. Course-native task categories were mapped to CDIO stages, with Operate interpreted as a representational and integrative phase enacted through final posters and presentations. Process behavior was analyzed using Sankey-style visualizations and explicit identification of backward CDIO transitions as loops. Results indicate that CDIO progression is predominantly directional but explicitly non-linear. Within-stage iteration accounted for 56.5% of transitions, forward transitions for 30.4%, and backward transitions for 13.0%. Backward transitions were concentrated primarily in the Implement stage, reflecting reframing triggered by technical resolution, representational demands, and constructability constraints. Remarkably, backward transitions were also observed from Operate, indicating that final presentations occasionally prompted reconsideration of earlier design or implementation decisions rather than functioning exclusively as terminal stages. Experiential results show consistently high perceived collaboration and goal orientation across tasks, with moderate-to-high levels of Grit and Vision. Vision was strongly associated with Purpose and Enjoyment, while Grit was closely related to Effort and Persistence.

KEYWORDS

Architectural engineering, Renovation, CDIO processes, Iteration, design loops, Standards: 1, 5, 7, 8, 11.

INTRODUCTION

The Conceive-Design-Implement-Operate (CDIO) framework is a globally recognized approach to engineering education that emphasizes integrated learning, professional competencies, and engagement with real-world engineering practice across the full project lifecycle (Crawley, Malmqvist, Östlund, Brodeur, & Edström, 2014; Malmqvist, Edström, & Rosén, 2020). Developed to address persistent gaps between theoretical instruction and professional application, CDIO has been widely adopted across traditional engineering disciplines, including mechanical, electrical, and software engineering, where it has demonstrated effectiveness in fostering technical competence, teamwork, and problem-solving skills (Bankel et al., 2003; Graham, 2018; Stachura & Bar-Eli, 2024). More recently, CDIO principles have begun to inform education in architecture and the built environment. Studies in architectural engineering, sustainable design education, and studio-based learning environments indicate growing interest in CDIO as a means of integrating design, technology, and lifecycle thinking (Selim, Mayhoub, & Abuzaid, 2025; Woźniczka & Widera, 2022). These developments suggest that CDIO offers a relevant framework for architectural engineering education, particularly where project-based learning, interdisciplinarity, and sustainability considerations are central.

Although CDIO is theoretically defined as a lifecycle framework, many curricular implementations and evaluations in engineering education continue to represent CDIO as a progression through discrete phases (Rodriguez Bernal, 2017). While such representations align with new-build engineering projects, they are less suited to renovation-oriented architectural engineering, where design–engineering processes are inherently iterative and constraint-driven. Renovation projects require continuous engagement with existing structures, historical and cultural values, regulatory frameworks, and evolving technical information, frequently necessitating reconsideration of earlier decisions as new constraints emerge (Douglas, 2006; Gil-Mastalerczyk, 2020; Plevoets & Van Cleempoel, 2019).

In architectural engineering education, renovation studios typically involve repeated cycles of interpretation, spatial reframing, technical resolution, and representational synthesis rather than a single pass-through predefined phases (Schön, 2017). Iteration and backtracking are therefore not indicators of process failure but integral features of competent renovation practice. Although CDIO literature conceptually acknowledges iteration, empirical educational studies continue to prioritize phase completion, learning outcomes, or competency mapping, providing limited visibility into how iterative processes are enacted in student work. As a result, the enactment of CDIO in renovation-oriented architectural engineering education remains underexplored, particularly with respect to how iterative process patterns relate to students' experienced agency, motivation, and collaboration. Existing studies (e.g. (Lenz, Diefenbach, & Hassenzahl, 2019; Renganathan, Shanthi Priya, Kumar, Thiruvengadam, & Senthil, 2025) rarely combine task-sequence analysis with experiential data in ways that make iteration empirically visible across a cohort.

This paper addresses this gap by examining how CDIO is enacted in practice within a renovation-focused architectural engineering studio through a combined analysis of task-level process data and task-based experiential indicators. By visualizing CDIO transitions, identifying backward loops, and relating these patterns to students' perceived Purpose, Control, Effort, Persistence, Enjoyment, and collaboration, the study contributes a process-sensitive interpretation of CDIO that aligns with the realities of renovation-based architectural engineering education.

METHOD

Research Design and Analytical Framework

This study employs a quantitative, process-focused survey approach in architectural engineering education, with building renovation as the empirical case. Renovation is viewed as an iterative design-engineering process influenced by current conditions, historical constraints, and collaborative decision-making. The CDIO framework functions as the main analytical perspective, not as a measurable variable, but as a process ontology that helps interpret students' task-level experiences throughout the renovation workflow.

Educational Context and Participants

Data were collected during the autumn of 2025 from 19 second-year students enrolled in a renovation-focused architectural engineering course in Jönköping, Sweden. Students worked in pairs on a project-based renovation brief involving historical analysis, spatial design, material considerations, and architectural representation of a formal industrial building turned into a boutique hotel. Across the course, 226 task-based survey responses were recorded in direct connection with specific project activities. Participation was voluntary, and all data were anonymized.

Task Categories as Units of Analysis

Analysis was structured around empirically encoded task categories, representing distinct modes of architectural-engineering activity that could recur over time: Concept and Moodboard, Historical Analysis, Site-plan and Volume, Floorplans and Elevations, and Poster and Presentation materials. These categories formed the primary units of analysis and were interpreted through the CDIO lifecycle.

CDIO Interpretation of Tasks

Concept and Moodboard and Historical Analysis were mapped to Conceive, with the latter emphasizing constraint-driven interpretation specific to renovation practice. Site-plan and Volume corresponded to Design, while Floorplans and Elevations represented a Design–Implement transition requiring technical and representational resolution. Posters and presentations were interpreted as Operate (late-stage synthesis outputs), functioning as integrative and communicative closure rather than building use.

Measures

All constructs were measured using five-point Likert scales (1=strongly disagree, 5=strongly agree). The survey captured perceived Purpose, Control, Effort, Persistence, Enjoyment, and Groupmate contribution. Two composite indices were computed: Grit (Effort + Persistence) and Vision (Purpose + Enjoyment), calculated only when both components were present. An online tool was built for capturing students' ratings (www.designtool.se).

Analytical Strategy

Descriptive statistics and Pearson correlations were used to explore relationships among constructs, interpreted as process-sensitive associations rather than causal effects. To capture non-linearity, task entries were ordered chronologically per student and mapped to CDIO stages. A CDIO loop was recorded when a transition moved backward in the ordinal sequence (Conceive → Design → Implement → Operate). Within-stage repetition was treated as iteration but not classified as a loop. Four loop types were identified: Design-Conceive, Implement-Design, and Implement-Conceive, and Operate-to-Earlier stage loops, reflecting cases in which late-stage synthesis and presentation activities prompted reconsideration of design or implementation decisions.

Methodological Positioning and Limitations

Loops were interpreted as meaningful indicators of constrained design reasoning characteristic of renovation practice, rather than as deviations from the CDIO framework. The study does not assess CDIO competencies or technical performance outcomes and relies on self-reported experiential data. As such, the findings should be interpreted as reflecting students' perceived engagement and process enactment rather than objective measures of design quality or learning achievement.

RESULTS

Descriptive statistics for all indicators are presented in Figure 1. Across the full dataset, mean scores for all experiential indicators exceeded the midpoint of the scale. Groupmate contribution yielded the highest mean value (M = 4.85, SD = 0.48, n = 226), indicating consistently high perceived balance of contribution within student pairs. Purpose also exhibited a high mean (M = 4.50, SD = 0.63), followed by the composite Vision index (M = 4.14, SD = 0.64). Mean Control was M = 3.98 (SD = 0.89), while Effort (M = 3.90, SD = 0.96) and Persistence (M = 3.97, SD = 0.82) demonstrated similar central tendencies. Enjoyment showed a mean of M = 3.78 (SD = 0.92), reflecting moderate to high affective engagement across tasks. The composite Grit index yielded a mean value of M = 3.93 (SD = 0.70).

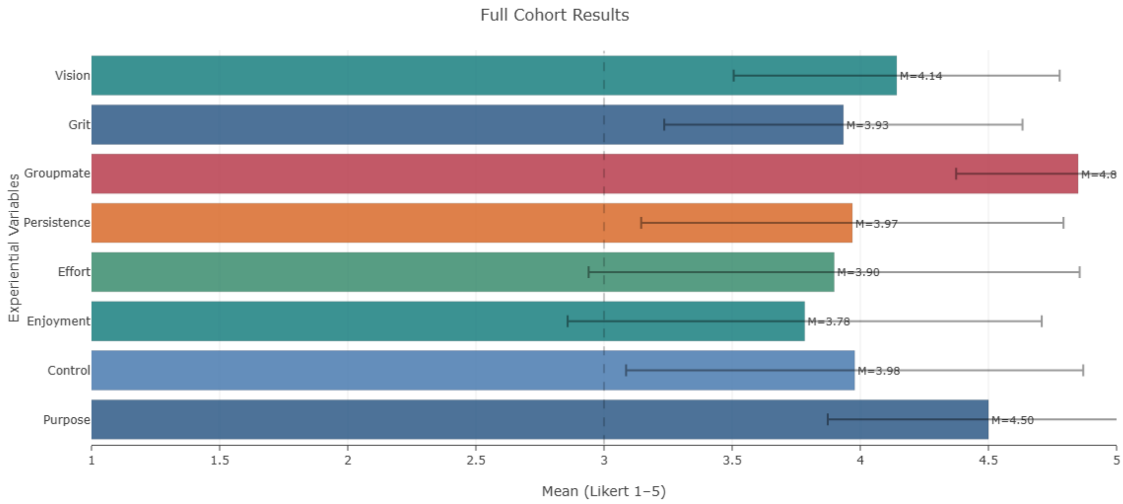

Figure 1. Full cohort descriptive statistics (N=226)

Task-Oriented Results

Considerable variation was observed across task categories (Figure 2), particularly for Purpose, Control, and Enjoyment. Mean Purpose scores ranged from M = 3.69 (SD = 0.70) during Historical Analysis tasks to M = 4.64 (SD = 0.64) during Presentation and Poster tasks. Control showed a similar pattern, with the lowest mean during Historical Analysis (M = 3.38, SD = 1.15) and the highest during Presentation and Poster (M = 4.44, SD = 0.77). Effort and Persistence demonstrated comparatively limited variation across task categories. Effort means ranged between M = 3.44 and M = 4.06, while Persistence ranged from M = 3.75 to M

= 4.08, indicating relatively stable work investment across different phases of the renovation process. Enjoyment exhibited greater task sensitivity, with lower mean values during Historical Analysis (M = 3.06, SD = 0.85) and higher values during Presentation and Poster (M = 4.44, SD = 0.77). Groupmate contribution remained consistently high across all task categories, with mean values ranging from M = 4.63 to M = 4.96 and low associated standard deviations. Composite indices reflected these task-level patterns. Vision ranged from M = 3.38 during Historical Analysis tasks to M = 4.54 during Presentation and Poster tasks. In contrast, Grit demonstrated a narrower range across task categories, varying between M = 3.70 and M = 4.00.

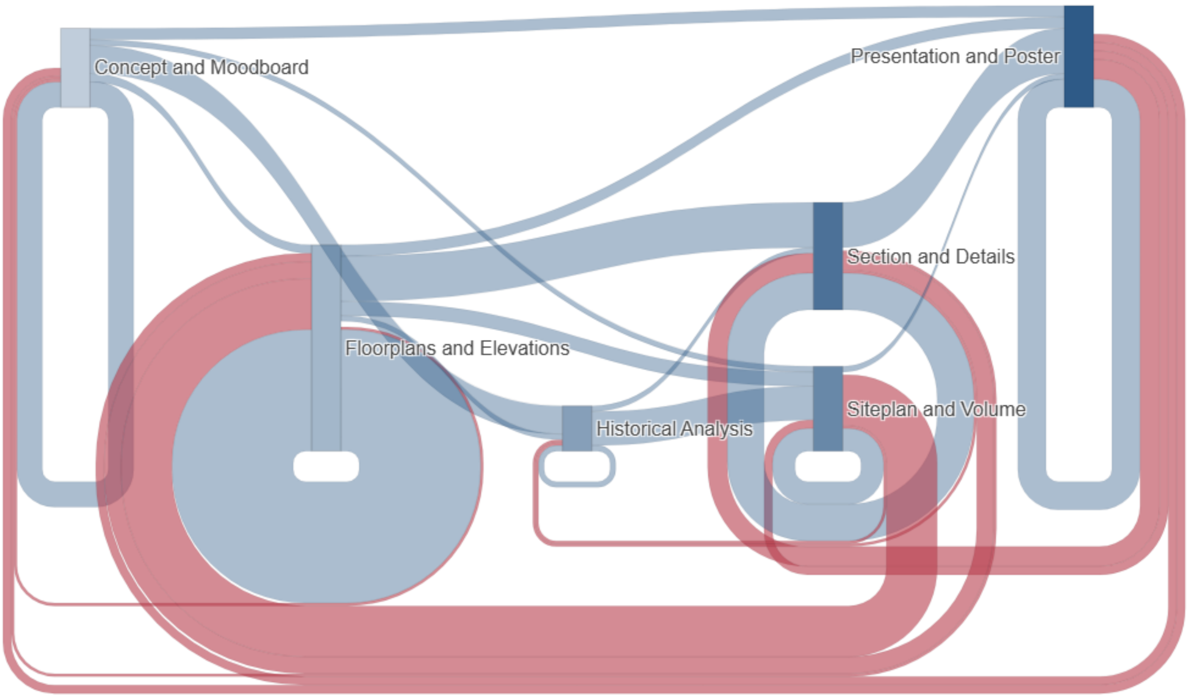

Figure 2. Static snapshot from an interactive Sankey diagram illustrating transitions between task categories; red flows indicate backward loops.

CDIO-Oriented Results

Tasks were analytically mapped to the CDIO stages (Conceive, Design, Implement, Operate), and descriptive statistics aggregated by CDIO stage are reported in Figure 3. Across all CDIO stages, mean values for all experiential indicators exceeded the midpoint of the scale, indicating generally positive perceptions of purpose, agency, effort, persistence, and collaboration throughout the renovation process. Process analysis identified 207 CDIO-aligned transitions across the cohort. Of these transitions, 117 (56.5%) occurred within the same CDIO stage, 63 (30.4%) represented forward movement to a subsequent stage, and 27 (13.0%) constituted backward transitions, indicating iterative returns to earlier stages. Backward transitions were not evenly distributed across stages. The majority originated from the Implement stage, reflecting iterative refinement triggered by technical resolution, representational demands, or constructability constraints. However, backward transitions were also observed from the Operate stage, as shown by red links returning from Operate to earlier CDIO stages. These transitions indicate that final presentations and posters occasionally prompted reconsideration of earlier design or implementation decisions, rather than functioning exclusively as terminal stages. Design-stage loops were present but less frequent, while within-stage iteration dominated the Conceive and Implement phases, suggesting sustained exploration and refinement rather than linear progression. Despite the presence of backward transitions, Operate remained predominantly an endpoint in the process structure, with most trajectories converging toward this stage.

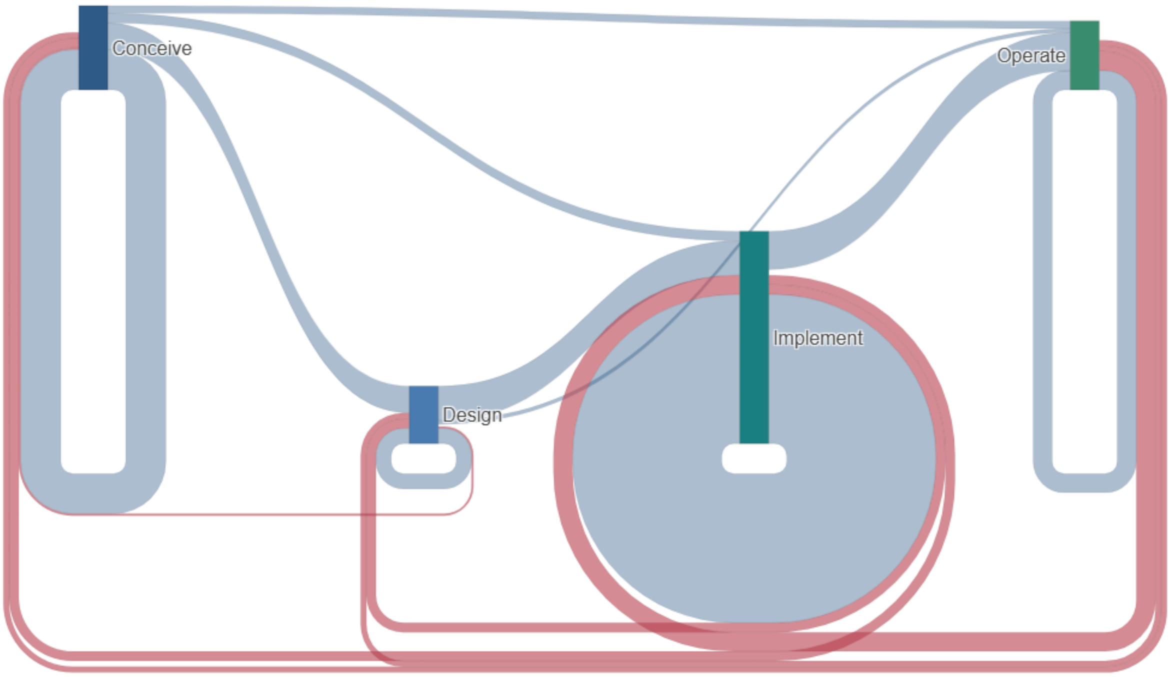

Figure 3. Static snapshot from an interactive Sankey diagram illustrating transitions between CDIO categories; red flows indicate backward loops.

Correlation Analysis

Pearson correlation coefficients among all indicators and composite indices are presented in Table 1. Vision demonstrated a strong positive correlation with Enjoyment (r=.88) and Purpose (r=.72), and a moderate positive correlation with Control (r=.44). As expected by construction, Grit showed strong positive correlations with Effort (r=.82) and Persistence (r=.74). Correlations between Groupmate contribution and other indicators were weak (|r| < .06), indicating limited association with individual experiential dimensions in this dataset.

Table 1. Correlations (r) among experiential indicators (p<.05)

	Control	**Enjoyment**	**Effort**	**Persistence**	**Grit**	**Vision**
Purpose	0.35	0.32	0.23	0.17	0.25	0.72
Control		0.38		0.15		0.45
Enjoyment				0.15		0.88
Effort				0.23	0.82	
Persistence					0.74	0.20
Groupmate						
Grit						0.17

DISCUSSION

This study aimed to examine how the CDIO framework is enacted in practice within renovation-oriented architectural engineering education, with particular attention to iterative process patterns and students' experiential responses across tasks and CDIO stages. The findings provide empirical support for interpreting CDIO as a predominantly directional yet explicitly non-linear process when applied to renovation contexts.

CDIO as a Directional but Non-Linear Process in Renovation Education

The process analysis demonstrated that while most transitions followed a forward or within-stage progression, a substantive proportion of backward transitions occurred across the cohort. The predominance of within-stage iteration and the presence of backward transitions indicate that renovation-oriented design-engineering processes involve sustained exploration and refinement rather than linear phase completion. These findings align with prior theoretical accounts of renovation practice, which emphasize constraint-driven reasoning, reinterpretation of existing conditions, and iterative negotiation between concept, design, and implementation.

Importantly, backward transitions were concentrated primarily in the Implement stage, suggesting that technical resolution and representational precision frequently trigger reframing of earlier design or conceptual decisions. This pattern supports the interpretation of loops as meaningful enactments of design reasoning rather than deviations from CDIO. The presence of backward transitions originating from Operate further challenges common educational representations of Operate as a purely end of project phase. In this study, final presentations and posters occasionally functioned as reflective and diagnostic moments that prompted reconsideration of earlier stages, reinforcing the view of Operate as an integrative and sense-making phase in educational contexts rather than a proxy for building use.

Task Sensitivity and Experiential Variation Across the Renovation Process

Task-oriented results reveal that students' experiential responses varied meaningfully across task categories, particularly for Purpose, Control, and Enjoyment. Lower scores during Historical Analysis tasks and higher scores during late-stage presentation activities suggest that interpretive and constraint-heavy phases may be experienced as more demanding and less immediately rewarding, while synthesis and communication phases provide greater clarity of purpose and perceived agency. These patterns are consistent with prior research on studio-based learning, which highlights differences in student engagement across analytical, generative, and representational tasks. In contrast, Effort and Persistence showed relatively stable mean values across tasks, indicating consistent work investment throughout the renovation process. This stability suggests that variations in enjoyment or perceived control do not necessarily translate into reduced effort, supporting the interpretation of renovation work as requiring sustained commitment regardless of task type.

Grit, Vision, and Collaboration in Renovation-Oriented CDIO Enactment

The experiential results further show moderate-to-high levels of both Grit and Vision across the cohort. The strong associations between Vision, Purpose, and Enjoyment indicate that students' future-oriented thinking and motivational alignment are closely tied to task meaningfulness and affective engagement. Similarly, the strong correlations between Grit, Effort, and Persistence confirm the internal coherence of these constructs as indicators of sustained execution capacity. Perceived Groupmate contribution remained consistently high across tasks and showed weak associations with other experiential indicators. This pattern suggests that collaboration was experienced as stable throughout the studio, rather than varying meaningfully across task types or CDIO stages. In the context of paired renovation projects, collaborative balance may therefore reflect course organization and team formation more than task-specific experiential dynamics.

Implications for CDIO Interpretation and Architectural Engineering Education

The descriptive statistics and correlation patterns provide context for interpreting the observed process structures. The consistently high levels of Purpose, collaboration, and sustained effort indicate that students experienced the renovation project as meaningful and engaging. In this context, the iterative task and CDIO loops are unlikely to reflect confusion or disengagement. Instead, they appear within a stable motivational environment characterized by sustained effort and balanced collaboration. Vision is closely associated with Purpose and Enjoyment, while Grit reflects sustained execution through Effort and Persistence.

These findings support a process-sensitive interpretation of CDIO that is particularly relevant for renovation-oriented architectural engineering education. Rather than treating backward transitions as inefficiencies or failures to progress, the observed loops can be understood as indicators of competent design reasoning under constraint. Making such loops empirically visible allows CDIO to be interpreted as an adaptive framework capable of accommodating iterative and exploratory practices characteristic of renovation work. From an educational perspective, the results suggest that CDIO-based curricula in architectural engineering may benefit from explicitly acknowledging and supporting iteration, particularly during implementation and late-stage synthesis. This may help align pedagogical models with students' lived experiences of design–engineering processes and avoid reinforcing overly linear interpretations of professional practice.

Implications for CDIO Standards

The findings of this study have implications for several CDIO Standards. Standard 1 (CDIO as Context) is supported by the empirical demonstration that renovation-oriented architectural engineering projects naturally enact the full CDIO lifecycle, although in a non-linear manner. The observed process loops suggest that CDIO functions as a contextual framework for learning when interpreted as iterative rather than sequential.

Standard 5 (Design–Implement Experiences) is reinforced by the concentration of backward transitions within the Implement stage, indicating that design–implement activities prompt meaningful reframing and technical reflection. These loops highlight the pedagogical value of implementation tasks as sites of learning rather than endpoints of execution.

Standards 7 and 8 (Integrated Learning Experiences and Active Learning) are reflected in the stable levels of effort, persistence, and collaboration across tasks, suggesting that students engage cognitively and affectively with renovation work through continuous integration of technical, conceptual, and representational knowledge.

Finally, Standard 11 (Learning Assessment) is informed by the study's use of task-level experiential indicators and process metrics. By making iteration and looping empirically visible, the findings point toward assessment approaches that recognize iterative reasoning and process quality as integral components of learning in architectural engineering renovation education.

Limitations and Directions for Future Research

This study is limited by its reliance on self-reported experiential data and a single course context with a relatively small cohort. While the task-sequence analysis provides insights into process structure, future research could combine similar methods with observational data, design artifact analysis, or longitudinal studies across multiple courses. Further work could also explore how different instructional strategies or assessment formats influence the frequency and character of CDIO loops. Despite these limitations, the present study demonstrates the value of integrating task-level process analysis with experiential indicators to advance empirical understanding of CDIO enactment in architectural engineering education.

ACKNOWLEDGEMENTS

The author received no external financial support for this work and gratefully acknowledges the students who participated in the study for their engagement and contributions in the Renovation course.

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BIOGRAPHICAL INFORMATION

Géza Fischl is an architect and an Assistant Professor in Architecture at the School of Engineering, Jönköping University, Sweden. He holds a PhD in the field of architectural and environmental psychology. His research focuses on architectural engineering education, design processes, human–environment interaction, and evidence-based decision-making. His work examines iteration, collaboration, and experiential dimensions of problem-based learning, often through CDIO-aligned and process-analytical frameworks. His current research interests include digital twins (DT) for renovation and operation, circularity and lifecycle thinking in the built environment, and AI-assisted cognitive digital twin architectures that support design reasoning, learning, and sustainability-oriented decision-making in architectural engineering education and practice.

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