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Exploring AI intervention points in high-school engineering education: a research through co-design approach

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Abstract

Purpose – Challenges in teaching the engineering design process (EDP) at the high-school level, such as promoting good documentation practices, are well-documented. While developments in educational artificial intelligence (AI) systems have the potential to assist in addressing these challenges, the open-ended nature of the EDP leads to challenges that often lack the specificity required for actionable AI development. In addition, conventional educational AI systems (e.g. intelligent tutoring systems) primarily target procedural domain tasks with well-defined outcomes and problem-solving strategies, while the EDP involves open-ended problems and multiple correct solutions, making AI intervention timing and appropriateness complex.

Design/methodology/approach – Authors conducted a six-week-long Research through Co-Design (RtCD) process (i.e. a co-design process rooted in Research through Design) with two experienced high-school engineering teachers to co-construct actionable insight in the form of AI intervention points (AI-IPs) in engineering education where an AI system can effectively intervene to support them while highlighting their pedagogical practices.

Findings – This paper leveraged the design of task models to iteratively refine our prior understanding of teachers' experiences with teaching the EDP into three AI-IPs related to documentation, ephemeral interactions between teachers and students and disruptive failures that can serve as a focus for intelligent educational system designs.

Originality/value – This paper discusses the implications of these AI-IPs for designing educational AI systems to support engineering education as well as the importance of leveraging RtCD methodologies to

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engage teachers in developing intelligent educational systems that align with their needs and afford them control over computational interventions in their classrooms.

Keywords Engineering education, Co-design, Artificial intelligence (AI), Engineering design process (EDP), Intelligent educational systems, Research through design (RtD)

Paper type Research paper

Introduction

The impact of artificial intelligence (AI) on education is increasingly recognized across disciplines ranging from computer science (Eguchi *et al.*, 2021), to language (Akgun and Greenhow, 2022), to physical education (Lee and Lee, 2021). AI-powered Intelligent Tutoring Systems (ITS) have been particularly impactful in educational contexts (Chounta *et al.*, 2022; Zafari *et al.*, 2022), supporting learners in applying known strategies to get to predetermined outputs (e.g., a correct answer to a mathematical problem) and intervening when tasks are not progressing toward that output. While such tutoring systems have shown significant promise in constrained problem spaces, like math, there is increasing interest in applying AI to more open-ended, problem-based educational spaces like high-school engineering (Hutchins and Biswas, 2024; Yang *et al.*, 2024).

In engineering classes, students engage in hands-on building and prototyping toward solving a design challenge. The specific projects created by students are not the key intended outcome of engineering education, however (Jin *et al.*, 2024). Rather, prototypes are a means through which students can foster an understanding of the engineering discipline and practice the Engineering Design Process (EDP), a series of iterative steps for ideating, refining, and executing a design (NGSS, 2013). Students engaged in the EDP are supposed to explore multiple potential solutions, meaning that a virtually infinite number of pathways to success are possible. Engineering teachers guide students through this exploration, and students document their progress and reflections in EDP logs. However, prior work shows that students have challenges in reflecting about and actively documenting their processes, which are critical skills in engineering (Moore *et al.*, 2016; Schimpf *et al.*, 2024). This work explores how AI can be integrated into teacher support technology that helps them engage their students in documentation and reflection practices throughout their engineering process.

A key challenge in designing an intelligent system for scaffolding students in engineering education is the need to support not a specific trajectory toward known solutions, but engagement in the process of exploring and testing potential solutions and providing students the freedom to fail and reflect on their design approaches and the challenges they encounter (Belghith *et al.*, 2023; Jin *et al.*, 2024). While experienced teachers rely on their intuition, knowledge, and experience to tailor their pedagogies to different students' needs and to recognize when and how to intervene effectively (Baptiste Porter, 2024), AI systems lack this capacity and need to be designed to intervene at specific points in ways that complement teachers' approaches and preferences. Designing an effective AI system that takes into account the complexities of an open-ended learning environment, requires determining the optimal moments for AI system intervention.

Our design team had initial intuitions about potentially effective intervention points based on experience as engineering education researchers, teachers, and AI developers. We conducted a Research through Co-Design (RtCD) process to validate, examine, and elaborate on these intuitions. We recruited two current high-school engineering teachers into our design team to conduct a six-week summer internship. Here, we present the process of engaging these teachers in task modeling to inform where AI systems can effectively support teachers and their students in open-ended exploration for engineering education in ways that uphold teachers' autonomy and prerogative in their classrooms and complement teachers' relationships with their students.

Related work

Engineering education at the K-12 level

Teachers' understanding of engineering (Moore *et al.*, 2022; Smith *et al.*, 2021) and their priorities (Belghith, 2023; Radhakrishnan *et al.*, 2021), as well as other practical constraints such as administrative requirements and state standards (Alemdar *et al.*, 2017; Mesutoglu and Baran, 2021) can shape how the EDP is taught. Currently, in the U.S., engineering education is not part K-12 teachers' formal training, and there is a lack of clarity regarding its implementation and academic standards (Jin *et al.*, 2024). So, while teachers consistently and effectively draw on their existing pedagogical content knowledge and strategies (Baptiste Porter, 2024) to create environments where students engage in practical applications of their engineering and design skills, they are constrained by the classroom environment, resulting in design problems that often lack authenticity and open-endedness (Moore *et al.*, 2022). In practice, engineers are often required to document their processes (Moore *et al.*, 2016) and reflect on their design decisions (Schimpf *et al.*, 2024); however, both of these critical skills are known challenges in engineering education. Schimpf *et al.* (2024) highlights that engaging in reflection provides students with opportunities for personal authenticity where they can draw on their backgrounds and experiences to inform their design approaches, which can reinforce students' development as engineers (Abreu *et al.*, 2021). Often, students also struggle with integrating and applying their theoretical knowledge from different disciplines (e.g., math, physics, social sciences, etc.) into practical applications, leading to bottlenecks in their design process that require timely and personalized teacher guidance (Liu and Yang, 2024). In addition, while design problems are valuable in surfacing opportunities for explicit instruction, they fall short if teachers do not seize those opportunities to engage students in reflections about the Nature of Engineering – "issues relevant to the structure of the engineering discipline: what engineering is, how it works, how engineers conduct their work, the relationship between engineering and other fields of study such as science, and how engineering influences and is influenced by society" (Pleasants and Olson, 2019). This deficiency in addressing the broader context of engineering results in less authentic student experiences and a discrepancy between the intended and actual outcomes of these activities (Jin *et al.*, 2024). A student may produce an excellent design artifact without following a rigorous design process or understanding its concepts or value, while another student may produce an incomplete artifact while following a systematic process and reflecting on it, fostering essential design skills (Schimpf *et al.*, 2024).

Intelligent educational systems present a potential avenue to assist teachers in facing the aforementioned challenges while supporting the open-ended and multidisciplinary nature of engineering (Belghith *et al.*, 2023) and teachers' preferred pedagogical response (Hutchins and Biswas, 2024). However, many open questions remain as to how to ensure that technology development efforts match teachers' pedagogical practices and support their experiences and the challenges they face.

AI developments in education

In recent years, AI tools and applications have increasingly been deployed in K-12 educational settings mainly through machine-learning and ITS systems (Salas-Pilco *et al.*, 2022; Zafari *et al.*, 2022). ITS have been actively explored for individualized learning support in computer-based instruction (Akgun and Greenhow, 2022; Salas-Pilco *et al.*, 2022). These systems are typically developed based on task models (Thórisson *et al.*, 2016). A task model outlines the steps (i.e. green paths) that one must take to complete a task, for all the ways to complete that task (e.g., solving mathematics problems, or navigation problems). More importantly, a task model also describes, implicitly or explicitly, the steps that lead to failure (i.e. red paths) which highlights opportunities for an AI system to intervene and correct students' underlying misconceptions in performing the task (VanLehn, 2006; Weitekamp *et al.*, 2020).

Prior research shows that AI offers several potential benefits to education, such as increasing the capacity of current K-12 educational systems (Greenhow *et al.*, 2021; Hrastinski *et al.*, 2019; Murphy, 2019) and supporting teachers in certain aspects of their open-ended learning environment (Riedl *et al.*, 2008; Taub *et al.*, 2018), empowering them to fully enact their pedagogical goals with fewer resources. AI applications can assist teachers with time-consuming and repetitive tasks (Zafari *et al.*, 2022) and in their decision-making, by providing real-time class status reports and personalized learning platforms (Salas-Pilco *et al.*, 2022). These applications can also augment instruction by providing students with timely feedback on their work, and alleviating teachers' workloads through automated assessment systems (Akgun and Greenhow, 2022; Crompton *et al.*, 2024).

While AI applications can save time and alleviate some cognitive burden for teachers, they represent only one tool in the teachers' toolkit (Akgun and Greenhow, 2022). Chounta *et al.* (2022) suggest that, while teachers perceive AI as an opportunity for education, they have a limited knowledge of AI and how it could support them in practice. It is also essential to recognize that AI tools do not operate in isolation; they influence and are influenced by evolving cultural, social, institutional, and political forces (Ko *et al.*, 2020). Prior work has shown that AI technologies in education lack cultural sensitivity which can impact minority groups and calls for AI to complement teacher interaction and decision-making, not to substitute it (Azzam and Charles, 2024; Zafari *et al.*, 2022). For the effective integration of AI technologies in education, it is crucial for development efforts to focus on culturally-sensitive tools (Azzam and Charles, 2024) and for educators to develop a better understanding of "what [AI] is, what it can do, and how to it can be incorporated into teaching and learning" (Crompton *et al.*, 2024, p. 263).

Eliciting teacher priorities through research through Co-Design

Efforts have been made to address these concerns through professional development (PD) opportunities for teachers to understand and incorporate AI tools in their classrooms, along with discussions on the ethical implications of these tools (Ali *et al.*, 2019; Zimmerman, 2018). However, many AI innovation projects fail to cocreate value for users. Oftentimes, those "failures can be traced back to problem selection and formulation" due to a lack of domain stakeholders' involvement in the early phases of AI development (Yildirim *et al.*, 2023b). While strategies like Research through Design (RtD) and participatory design's value are recognized in the creation of educational technologies, sociotechnical systems, and interventions that sufficiently meet teachers' and learners' needs (Cober *et al.*, 2015; DiSalvo *et al.*, 2017), the unique features of AI introduce challenges to applying participatory design to AI development (Donia and Shaw, 2021) such as AI's explainability and AI prototypes being time- and resource-consuming to develop (Bratteteig and Verne, 2018). Various fields of design research are actively exploring new approaches, tools, and guidelines specific to improving participation in the design of AI (Birhane *et al.*, 2022; Loi *et al.*, 2018; Yildirim *et al.*, 2023b), but there remain limited methods for co-designing AI with novice stakeholders (Yang *et al.*, 2024). To create new intelligent systems to support and empower educators to effectively enact their pedagogical strategies, it is critical to explore new ways of involving teachers in the design of these systems through design-based participatory approaches (Hutchins and Biswas, 2024; Yang *et al.*, 2024).

RtD is a form of design inquiry where design practice produces new and valuable knowledge through an explicitly reflective interpretation and reinterpretation of problems and solutions (Zimmerman and Forlizzi, 2014). On the other hand, co-design is a collaborative process where designers and non-designers harness their collective wisdom by "shar[ing] and combin[ing] ideas and knowledge" around a common design artifact (Steen, 2013). While RtD focuses on the construction of new knowledge and perspectives through the practice of design, co-design highlights the importance of stakeholders' participation. Together, the co-design process provides a participatory dimension to RtD by involving teachers as members of the design team at the initial phase of the project to co-construct actionable insights on how AI technologies can effectively support classroom pedagogy. We name this process Research through Co-Design (RtCD). We grounded our RtCD process in known challenges and assumptions about technology development derived from our experiences and the prior literature (hereafter collectively referred to as our *conjectures.* Instead of requiring teachers to have an understanding of AI, we focused on designing an educational experience based on the teachers' experience at a level of specificity from which we could then derive spaces where technology can effectively intervene without undermining the teachers' or their students' autonomy. We used task modeling as a design tool to juxtapose our conjectures against the practical experiences and expertise of teachers as revealed during the RtCD process. This iterative process allowed us to refine our conjectures into specific opportunity points amenable to AI intervention.

Significance

To design an intelligent educational system that matches teachers' current needs in their engineering classrooms, maintains teachers' preferred pedagogies, and supports their students' creative and reflective processes, we investigate the following research question:

> *RQ1*. Where, in the high-school engineering education space, can an AI system intervene to provide support that aligns with the teachers' pedagogical goals and practices?

We present three potential AI intervention points (AI-IPs) for engineering education that are grounded in data collected during our RtCD process where we found evidence of the teachers' experiences reinterpreting, challenging, or extending our conjectures about the design.

This paper makes the following contributions:

- We present a different approach, RtCD, for engaging teachers who are novices in AI in the early phases of designing an intelligent educational tool through the combination of RtD and Co-design.
- We identify three potential intervention points where AI can intervene effectively in an open-ended educational context in a manner that does not undermine the teachers' autonomy and decision-making and directly addresses their current needs in their classrooms. These intervention points can also be adapted for open-ended educational contexts other than engineering.
- We highlight a few challenges remaining in high-school engineering education in relation to prior work on engineering education through deep reflections with teachers.

Methods

Research context and participants

The RtCD process took place in the summer of 2022 as part of a six-week teacher PD internship program hosted by the K-12 outreach and research center at a major university in the Southeastern U.S. Teachers from the metropolitan area apply to the summer internship program to work with higher-education STEM faculty and educators on sponsored STEM research projects related to their content area. Teacher interns work directly with faculty on their projects as well as engage in PD activities such as attending guest lectures and field trips with other educators in the program. We intentionally selected two experienced high-school engineering teachers with diverse backgrounds as members of our design team, in an attempt to capture a range of experiences and priorities. Teachers were compensated with a stipend for their involvement.

Macie (pseudonym) has a Specialist degree in Curriculum and Instruction. She has 14 years of experience teaching engineering classes and courses in computer applications, business, and manufacturing at the K-12 level. She has been chairperson and curriculum lead in her departments and school districts, during which time she developed engineering curriculum across the school district, supported interdisciplinary STEM initiatives including project-based learning, and collaborated with the Technology student Association (TSA) (*Technology student Association*, n.d.), where she also has a leadership role.

Stanley (pseudonym) came to teaching through the Troops to Teachers program after retiring as a Colonel from the U.S. Air Force, with experience as a fighter pilot and applied aerodynamics instructor. His Bachelor's degree is in political science, and he held executive positions in multiple companies in the manufacturing industry before earning an engineering and technology certificate and transitioning to classroom teaching. He has 7 years of experience teaching engineering at the middle and high-school levels and has been elected as a technology teacher of the year.

These teachers joined the academic research team comprising faculty members in the learning sciences, AI, and engineering education research, a learning sciences PhD student, and research scientists in educational research and evaluation. Researchers also have past experiences as K-12 teachers, collaborating with intern teachers, and deploying practical educational interventions in K-12 schools.

Study design and data collection

Over the six weeks of the program, the team participated in 11 *research blocks* (see Table 1), which consisted of sessions ranging from two to four consecutive hours dedicated to research activities, as part of the RtCD process. The activities consisted in authoring and analyzing different EDPs and design challenges, brainstorming AI technologies and discussing technology limitations and other considerations, creating and discussing curricula and flowcharts that document teachers' and students' tasks, responsibilities, challenges, resolutions strategies, and technology usage for each step of the EDP, and developing specific learning objectives for each step of the EDP along with their corresponding measures of success. The activities all worked toward the design artifact of a task model, which was employed here as a design and reflection tool. The co-design of task models of students' activities and challenges in engineering allowed the design team, including teachers, to make their wealth of knowledge and experiences explicit at a level of specificity that can serve as a basis for identifying effective AI system designs. More specifically, we focused on surfacing teachers' extensive, implicit knowledge and experiences to refine our existing understanding of engineering education into AI-IPs.

Table 1. Research blocks throughout the six-week RtCD study with their respective purpose

Week #	Research block #	Title	Purpose
2	1	EDP models	Exploring their understanding of and approaches to the EDP and discussing different EDP models
2	2	Design challenge properties	Discussing the development of design challenges, their components, and properties
2	3	AI imaginary	Brainstorming and discussing a science-fiction version of AI in an ideal world
3	4	Curriculum Mapping P1	Creating and discussing a curriculum for a new design challenge with a detailed outline for the task, teacher responsibilities, student responsibilities, student goals, teacher goals, and deliverables per class period
3	5	Curriculum Mapping P2	Integrating both curricula into one and outlining anticipated painpoints and technology usage for each task/class period
4	6	Flow chart challenges	Using a flow chart developed by the researcher, documenting specific challenges faced by students when transitioning from sketching to initially building (identified as one of the most challenging phases by the participants)
4	7	Flow chart resolutions	Revisiting the flow chart to document resolution strategies for each challenge
5	8	Learning objectives	Developing specific learning objectives for each step of the EDP in practice and discussing what success means in an engineering classroom and how to assess it
5	9	Evidence statements	Listing and discussing all the evidence and deliverables used to measure achievement of each learning goal
5	10	Task models	Consolidating all prior discussions into a task model Starting from each learning objective and its corresponding evidence, outlining a path of tasks to achieve the learning goal
5	11	Task models review	Outlining all potential/anticipated pitfalls in each path of tasks Reviewing and discussing final task model

Source(s): Authors' own work

Research blocks were led by the first author with support and participation from other members of the project team and were done by both teachers in a combination of individual and group work. Following these blocks, the teachers also completed independent written reflections to contribute their own framing to the activities. Audio recordings and photos were taken during the 11 research blocks and all artifacts produced from the RtCD activities, including written reflections, curricula designs, presentation slides, flow charts, and draft task models were collected. Throughout the study, the first author also maintained typed notes and research memos where they documented any new, surprising, or unexpected statements by the teachers. Reflections and notes were reviewed with the teachers to ensure the researchers were appropriately interpreting and documenting their experiences.

In addition, teachers attended discussions and presentations with the team (e.g., presentations on research in AI) toured campus research facilities, completed PD activities (e.g., collaborative institutional training initiative training, and designing an action plan for their upcoming school year), and met one-on-one with the team over the course of the summer to allow them to articulate their perspectives without the pressures of group dynamics.

Data analysis

The RtD dimension of our process necessitates a continuous reevaluation of our perspectives, ensuring alignment with the evolving context (Zimmerman and Forlizzi, 2014). As part of this process and to articulate AI-IPs that directly address teachers' needs, we made explicit all relevant knowledge and critically revisited our initial *conjectures* – the hypotheses, assumptions, and intuitions we brought to the work from prior literature and experiences as articulated in our research proposal – against the knowledge cocreated with the teachers during the RtCD process.

To make these comparisons, the first author, who was not involved in authoring the research proposal, extracted all conjectures about engineering education from the proposal. These conjectures (n = 41) were then inductively categorized into three distinct classes of conjectures and further subcategorized (see Table 2). The three categories are:

(1) conjectures related to documentation practices in the classroom (n = 9);

(2) conjectures concerning the implementation of the EDP in the classroom (n = 19); and

(3) conjectures associated with the creation and integration of Artificial Intelligence (AI) in the classroom (n = 13) (see Table 2).

All authors, including all the research proposal authors, discussed and provided feedback on the final list of conjectures, agreeing that they captured the motivation and framing of the research.

The next step was to identify points during the RtCD process where any of our conjectures were discussed and/or challenged. We cross-referenced our conjectures with the research memos created throughout the six-week RtCD process and found that the majority of conjectures were discussed in four of the 11 research blocks (equalling 6 h and 28 min of recordings). One of the research block recordings had previously been transcribed and partial transcriptions and notes were generated for the remaining recordings. We carefully reviewed the research block recordings and transcriptions to assess the extent to which our conjectures aligned with the teachers' statements. Using this process, we tagged the conjectures using the following schema:

- *True* (i.e., the initial conjecture was sustained by teachers and not challenged);
- *True And […]* (i.e., indicating that teachers highlighted additional factors to consider that extended beyond the initial conjecture);
- *True But […]* (i.e., indicating that the actual situation was more intricate and nuanced than initially assumed); and
- *False* (i.e., the initial conjecture was refuted by the teachers).

Seven conjectures were tagged as *cannot say* and excluded from our final data set as they extend beyond the scope of our discussions with teachers, such as statements referring to the evaluation of the system once it is developed. Conjectures tagged as *True* consisted of general, high-level information about engineering education such as "a lot of engineering classroom instruction is done in physical domains (e.g., makerspaces and hands-on prototyping)."

Table 2. Categories and subcategories of conjectures extracted from the original research proposal with corresponding examples

Category	Sub-category	Example statement from research proposal
Documentation	Generation	“students generate artifacts such as reports, logbooks, notes, drawings, and prototypes that teachers use to evaluate the student’s design learning”
	Use	“these artifacts are used primarily for grading rather than pedagogical guidance, students often create the physical documentation in a post-hoc fashion rather than in real-time”
	Value	"Requiring a document in which students are tasked with recording their work … has been offered as part of good practice in engineering instruction”
	Challenges	“Students were also reluctant to engage in self-reflection in their documentation of activities”
EDP implementation	Feedback	“prototyping and testing … are easier for teachers to assess”
	Teacher challenges	"teachers are likely to develop expertise about pathways that will or won’t work once they’ve taught a particular design project more than once. As it stands, that *expertise cannot be delivered to students without face-to-face feedback*”
	Student challenges	"*students are inclined to skip steps* of the process, ignore tasks, or take a wrong path through the EDP"
AI creation and integration	Task model creation	"One can think of the process of solving a task as a state machine where the student must take actions to transition through a number of intermediate states before arriving at the solution. *Some of these trajectories—sometimes called green paths—lead to successful completion, while some trajectories —red paths—are known errors*”
	Technology integration challenges	"There are two challenges that exacerbate [technology integration]—… *the large amount of work required for teachers to develop novel design challenges and projects*, including accompanying worksheets, design logs, and assessments”
	System design process	"With [internship program name] teacher collaboration, *we will identify the basic EDP principles and how to recognize them algorithmically*”

Source(s): Authors’ own work

This analysis focuses on conjectures coded as *True And*, *True But*, and *False* which indicate areas where the teachers’ expertise surfaced additional information about engineering education that challenged our initial understanding in specific ways. Once these *True And, True But, and False* conjectures were identified, the research team–including experts in AI and the learning sciences–met to reflect on how this new understanding of the space can inform specific points where AI intervention can be effective. The team deduced three potential AI-IPs, as described next.

Findings

Artificial intelligence-intervention point 1: Ensuring adequate documentation

The known challenges of student documentation were prominent in our preliminary conjectures about this work. Adequate information must be documented by the students at each step of the EDP in order for students to generate final portfolios or reports that adhere to a variety of requirements (e.g., turning in their portfolio in accordance with their teachers' assignment requirements). Multiple *True And* conjectures about documentation practices informed AI-IP1. For example, one conjecture related to documentation generation, stated that "[t]hroughout the process, students generate artifacts such as reports, logbooks, notes, drawings, and prototypes that teachers use to evaluate the student's design learning." While this statement is true, our RtCD process highlighted that documentation generation is also driven by the competitions students and their teachers take part in such as the TSA (TSA, 2024) national engineering design competitions which requires full documentation. For example, Macie states that she focuses all her first-year students on preparing and generating documentation portfolios that are up-to-par for TSA competitions. In addition, Stanley states that documentation is also important to protect his students' intellectual property. When talking about a group of students he is mentoring to file a patent, he states:

> I'm in the middle of that [patent filing], without proper documentation from the kids, because they were not in my class […] they came to me with an all ready conclusion that 'we've won this and now what do we do?'

Our conjectures also addressed how documentation was used, specifically that "these artifacts are used primarily for grading rather than pedagogical guidance, students often create the physical documentation in a post-hoc fashion rather than in real-time, providing only a partial picture of the design process." Macie elaborated on this idea with the insight that, in student group work, the documentation "*gets muddy*" (Macie) because the teacher cannot attribute individual credit and check how each student is individually thinking about the problem.

The documentation process is a clear opportunity for AI intervention. An intelligent system could assist teachers in ensuring that students are generating documentation at regular intervals and that each step's process is thoroughly documented before students advance to the next step. This documentation can be evaluated by the system for commonly missing content, such as a lack of dimensions in technical drawings, and cue students with specific reflection prompts such as "take some time to think about your dimensions; how high will your design be?" To assist with student evaluations, an AI system can intervene to differentiate individual authorship of drawings, notes, and other artifacts by, for example, automatically logging authorship at the time of upload, requesting a short memo from each team member on the artifact, or requiring team members to outline individual contributions. These reminders and oversight tasks currently fall to the teacher; offloading them to an AI can free the teacher's attention to focus on more substantive feedback to students.

Artificial intelligence-intervention point 2: generating context-specific scaffolds from ephemeral talks

The second AI-IP refers to generating context-specific scaffolds for students from their ephemeral talks with their teachers throughout their engagement with the design problem. As students plan, construct, and evaluate their solutions to a design problem, they will encounter some challenges and failures and will require real-time feedback and guidance from their teachers. Our prior work (Belghith *et al.*, 2023) and initial conjectures show that students do not generally like to admit when their designs are not performing well or admit failure. In addition, students are reluctant to engage in self-reflection in their documentation of activities; they would record that a problem had occurred, but often do not reflect on why the problem occurred or how to address it. To augment the teachers' ability to provide this guidance and assessment in a classroom where they cannot be everywhere at once, we initially assumed that an intelligent creative support assistant could scaffold and guide teachers in authoring this guidance specific to the current design problem and creating automated tutors at hand that provide feedback to students at the proper times. However, our RtCD process highlighted that this advice is highly context-dependent; it varies depending on the design problem, on the individual student's design approach and where they are in the EDP, as well as their prior knowledge and needs, among many other factors. Capturing the wealth of variables in a classroom that result in a specific piece of advice and modeling them algorithmically is very complex, particularly when such guidance is often provided in the form of ephemeral talks between teachers and students.

During our RtCD process, the teachers recognized moving beyond failures through self-reflection and iteration as challenging for students. Both Stanley and Macie employ some form of check-in (e.g., daily check-ins, progress meetings) with their students to redirect them toward and reengage them with the EDP. Macie added that students will get off-task because the building process is not progressing as planned, instead of attempting to move beyond the failure. She resolves this by explicitly asking the student teams to "*walk back through the process.*" Our RtCD process also highlighted that students do not perceive iteration as productive. Iteration during the earlier stages of the EDP is perceived as "*tedious*" (Macie) and leads to students getting bored as they are eager to reach the building phase. Iteration required when the prototype fails to perform is perceived as a failure and leads to students getting disengaged and discouraged.

We also found that teachers' engineering design problems vary greatly in length. While Macie tends to select longer design projects that span a number of weeks, Stanley often prefers daily design challenges that can be completed in one to two class periods, especially for his more novice, 9th grade students. In Stanley's case, trying to preempt all of his students' challenges and identify all areas for feedback would take longer than completing the actual activity. More importantly, both Macie and Stanley highlighted the need to reflect and be flexible in adapting to their changing classroom environments:

> Because kids are going to challenge you, they want to […] they're smarter than you are. […] that's why I said sometimes I may have to go back and put in an extra word based off of something some kids said in first period that I didn't think about, and I say, Okay, let me hurry up and put that in there before second period sees it, or I'm gonna have those same issues (Macie).

Stanley adds that these reflections may not come to fruition until the teacher gets to know their students better:

> [the design challenge is] going to have to be changed as you go, but that's what teachers do is try to learn who their students are, what their capabilities are.

Much of these reflections, changes, and guidance happen through ephemeral talks or interactions between students and teachers. As Macie shared, while the administration, students, and their parents expect grades on concrete artifacts produced by the students, teachers are also constantly evaluating their students informally. She mentioned daily check-ins with students as a great formative assessment and a way to redirect students toward the appropriate next step or iteration and to resolve the challenges they are facing. However, she added that it is complicated to implement with a classroom of about 30 students or when student teams are working on different design projects and need different amounts of help.

Throughout the RtCD process, ephemeral interactions and talks between students and their teacher repeatedly surfaced as a space where most of the pedagogical interventions from the teachers take place and where the decision making and problem-solving around design projects happens. However, due to their nature, these interactions are rarely, if ever, documented and thus reflection opportunities are lost, and formal assessments disregard them. An intelligent educational system could assist in capturing, documenting, and indexing these interactions to use them productively in accordance with the design problem brief. For example, a computational tool could summarize these ephemeral talks and use them as a basis to scaffold self-reflection opportunities for students or highlight important reminders and suggestions for students based on their past conversations with their teachers. More specifically, the tool could be used for students to set a number of goals for a class period and keep them on track to accomplish those tasks while generating self-reflection prompts aimed at helping them preempt known problems. For example, students could set "brainstorming ten design ideas" as their goal and the system could prompt them with self-reflection questions about whether their design ideas respect the requirements and constraints of the design brief, whether the appropriate materials and tools are available for prototyping such ideas, or about the students' individual thoughts about each idea and potential issues they can foresee with each design. During iteration phases, the system could reengage students with the EDP by suggesting potential next steps based on teachers' ephemeral guidance and/or students' documentation. In addition, an intelligent tool could also leverage these ephemeral interactions to assist teachers in their self-reflection exercises and highlight areas where changes to the design problems could be beneficial.

Artificial intelligence-intervention point 3: preventing or resolving disruptions

The third AI-IP refers to guiding students through prevention or resolution strategies for small disruptions in the process where teacher interaction is not strictly necessary.

Our initial conjectures expected high-school engineering students to grapple with failure. Students are not expected to achieve success on their first attempt at a design problem; rather, they are expected to experience some failures, practice their ability to iterate on designs and prototypes, revisit their documentation and engineering knowledge, and authentically engage in the problem-solving process. These productive failures (Kapur, 2008) are core to engineering practice and beneficial to overall learning, even if they may cause some deviations from the teachers' original lesson plans. We also expected other, disruptive failures (Belghith *et al.*, 2023) which are defined as deviations from the teacher's plan that may not have pedagogical value. For example, students generating documentation in a post-hoc manner or teachers and students skipping the earlier steps of the EDP (i.e. the phases leading to prototyping, such as the problem definition, background research, and ideation phases) because they were less interesting, harder to grade, and/or difficult for the teachers to understand.

When trying to define all failures during our RtCD process, teachers primarily identified disruptive failures, such as classroom practices failures, failure to engage with the EDP, and failures to use materials properly. Classroom practices failures consist of students' behavior problems in the classroom. Macie and Stanley described instances in which students did not follow classroom rules (e.g., being on their phones, trying to rush through a task by skipping steps), did not follow safety protocols around tools and equipment properly, and questioned teacher authority. For example, Macie recalled instances where "*students request to use a shop machine that no one in the group has been trained on*." Stanley also reports an interaction with a student challenging his authority, to whom he said:

> If you would spend even 10% of the time that you are trying to beat me on exactly doing what you're supposed to do, then you would be very successful.

In this case, the student was using the motivation behind the design challenge as a means of confrontation that did not have to do with the activity itself. Macie experienced similar issues, adding that:

> You're also trying to teach them that it doesn't matter if you're an engineer or not, if you work for somebody other than yourself, where you don’t make the rules, you're going to have to follow their [rules].

In these cases, the teachers were preparing for students’ motivation “failure,” which is common across all classroom activities, not just engineering design.

Another failure that both teachers mentioned related to students trying to circumvent completing the steps and/or substeps of the process and students feeling bored or lost if not enough guidance is provided. Macie said that, while she strives for her design challenges to be “*student driven*”, she has to set rules and restrictions in place mandating how the EDP is used, otherwise students will try:

> To circumvent the process, which some of them do, because […] they're gonna say, well, she didn't say we couldn’t use this. So I'm gonna do this and get it finished in five minutes, as opposed to work in the process and doing what I asked you to do.

A related issue that Macie described was when students are not interested or if not enough scaffolding is provided by the teacher, they become bored or feel lost. Stanley adds this question from the students’ perspective as a sanity check:

> If I put all of my time, they say, into this instead of being on my phone on a game, is there a reason that I'm doing it?

While we expected the earlier phases of the EDP to often be skipped, we found that, typically, it is because, in their preparations, engineering teachers often package enough materials (i.e. design briefs with background information, worksheets, list of materials) for their students to get started in a manner that allows students to skip or not engage authentically in the earlier steps of the EDP, sometimes even making potential solutions readily apparent. For example, Macie mentioned that, when selecting an engineering design problem, she will “*foresee the questions that [students are] going to have*” and needs to complete her own background research to best answer all of their questions during the “Ask” phase. She added that failing to answer the students’ questions will confuse them and may disengage them from the problem. While she may not sketch solutions herself, she will search for different solutions online to guide her students toward possibilities. In addition, Stanley stated that his less-experienced, 9th-grade students expect worksheets and specific requirements, and deliverables, repeatedly asking the question “*what do you want us to do?*” at each stage. Further, Macie also adapts her scaffolding and lesson plan to the class schedule and mood, sharing that morning and after-lunch classes tend to have energetic, hyper students, while during end-of-day classes, students tend to be tired and bored which leads to students having different needs and engagement levels.

In addition, both Macie and Stanley mentioned instances of students trying to use unapproved materials, or overusing and destroying materials available to them. Stanley explains that “*you got to have a materials list somewhere, or they’re just gonna take everything you have and destroy it*.” As noted by Stanley, these disruptive failures lead teachers to respond by over-constraining their design projects, ultimately restricting the possible solution space, reducing inventiveness and creativity and limiting the opportunities for productive failures.

In these cases, an intelligent system ought to distinguish between productive failure and disruptive failures. While the computational tool could allow students the freedom to grapple with productive failures, it can also alleviate some of the teachers’ burdens in addressing disruptive failures, freeing some of their time and effort to focus on coaching their students through productive failures and authentic engagement with the EDP. For example, the intelligent system could provide reminders or nudges to students if they are attempting to skip some EDP steps, or notify teachers by flagging student teams that have not completed tasks in a while. The system could also leverage gamification to encourage engagement, such awarding points tied to leaderboards and badges for milestones completed on time. In addition, the tool could encourage engagement by highlighting the real-world relevance of the design problem. For inappropriate tools and materials use, the system could verify that students have completed safety protocols or training and notify teachers accordingly and match the available materials and quantities from the design brief to the students' envisioned prototypes. By supporting teachers in addressing some of these disruptive failures, teachers' attention can be partially freed to support more advanced skills and content.

Discussion

The effective integration of Artificial intelligence in high-school engineering education

Engineering education continues to face challenges (Jin *et al.*, 2024; Schimpf *et al.*, 2024), including gaps in (1) documentation, (2) reflection, (3) the underutilization of teacher-student ephemeral interactions, which are vital for scaffolding and formative evaluation, as well as (4) disruptions often caused by disengagement and lack of motivation. While AI tools in education are rapidly advancing and offer novel opportunities (Crompton *et al.*, 2024), they cannot serve as blanket solutions to these challenges (Zafari *et al.*, 2022). AI technologies have profound impacts on teachers, students, and the broader educational context. Teaching and learning are fundamentally human-centered processes, and the integration of AI must align with teachers' pedagogical practices, respect their decision-making, and support their relationships with students. Furthermore, the design and integration of educational AI tools must acknowledge and respect the diverse cultural and social backgrounds of students, avoiding one-size-fits-all applications that risk marginalizing minorities and erasing cultural identities (Azzam and Charles, 2024; Flint and Jaggers, 2021).

In this research, we identify specific intervention points where AI can be helpful without undermining teachers' pedagogical approaches or students' creativity and problem-solving. Our findings highlight the potential of leveraging underutilized data—such as documentation, reflections, and ephemeral teacher–student interactions—not only to keep students engaged but also to encourage deeper integration of these interactions into their independent problem-solving and design processes. Intelligent systems can support documentation quality by prompting students to document regularly, reflect on design decisions, and ensure thoroughness before moving to subsequent steps. Teachers, in turn, can use these systems to track progress, differentiate authorship, and identify students needing additional support.

Crucially, our approach does not seek to reduce teacher–student interactions but to reinforce their integration into students' workflows. Nor do we aim to eliminate low-level tasks, exploration, or failure, as these are essential for students developing problem-solving skills and learning from their mistakes. Instead, we propose systems that differentiate between productive failures (Kapur, 2008), which foster learning, and disruptive failures (Belghith *et al.*, 2023), which often stem from disengagement or insufficient guidance. By providing timely nudges and leveraging gamification, these systems can reengage students and notify teachers of students requiring motivational support. By assisting with these pedagogical efforts, we aim for teachers' attention to be partially freed and allow them to focus on fostering advanced skills and deeper discussions about engineering as a discipline (Jin *et al.*, 2024), integrating students' cultural backgrounds into their learning (Abreu *et al.*, 2021), and addressing the ethical dimensions of using technology in engineering (Azzam and

Charles, 2024). By aligning AI tools with these pedagogical efforts, we aim to enhance both teaching and learning experiences while preserving their human-centered nature.

Employing RtCD approaches in the participatory design of AI technologies

The process of developing technological artifacts in human-computer interaction differentiates between sketching, or ideating to *make the right thing* and prototyping or iteratively refining to *make the thing right* (Bill Buxton, 2007; Yildirim *et al.*, 2023b). Many AI projects are creating tools misaligned with stakeholder needs. Existing resources, such as human–AI guidelines, provide limited support for identifying problems where AI solutions are optimal (Yildirim *et al.*, 2023a). In addition, leveraging participation in the design of AI also presents challenges, such as the teachers' lack of knowledge about AI and its capabilities (Bratteteig and Verne, 2018).

To *make the right thing*, we propose identifying precise points for AI interventions that assist teachers and students without disrupting or subverting their educational experiences or their classrooms' cultural contexts. This approach informed our RtCD study, combining RtD and co-design to surface teachers' lived experiences as critical knowledge for co-defining AI-IPs and augment rather than replace or modify their pedagogical approaches.

We involved teachers through a six-week PD internship. This strengthened our collaborative relationship and positioned teachers as co-designers rather than potential end-users. Using task models, common in AI development yet beginner-friendly, as a design and reflection tool was valuable for teachers to grasp some AI concepts and to elicit their tacit knowledge at a level of specificity that AI developers can act upon. Guest lectures and discussions with AI experts within RtCD activities furthered teachers' PD in AI and supported them in critical reflections on their experiences in relation to AI system design. Such opportunities can help pre- and in-service teachers manage AI's classroom integration and contribute meaningfully to its development (Akgun and Greenhow, 2022).

Limitations and future work

Some limitations of our work include the small participation numbers due to the length of our study. As such, our work focuses on depth over breadth in demonstrating how our RtCD process can be implemented to identify AI-IPs in the early stages of an intelligent educational system while leveraging participatory approaches. For future RtCD efforts, we emphasize establishing lasting collaborative relationships with educators, students, and other stakeholders from the earliest stages of problem formulation in the design of educational AI technologies. This collaboration should aim to critically reflect and reinterpret current educational experiences and technologies, exploring how they "could and should be" (Zimmerman and Forlizzi, 2014) and to bring "form, function, and clarity" to future AI systems (Loi *et al.*, 2018). Moreover, co-design efforts must uphold power dynamics that position teachers and students as co-creators, emphasizing their lived experiences and expertise as crucial knowledge sources (Berditchevskaia *et al.*, 2020; Bondi *et al.*, 2021; Zimmerman and Forlizzi, 2014) and support their PD through activities such as guest lectures and in-depth discussions with AI experts. We also recommend grounding design processes and discussions in techniques, such as task modeling, in ways that highlight stakeholders' lived experiences, tacit knowledge, preferred pedagogical approaches, and needs. This can ensure that design techniques are accessible for novices in AI yet allow for insights and design conjectures to be co-constructed at a level of specificity that AI developers can grapple with. Future work should also implement and evaluate our RtCD approach in additional educational contexts.

Conclusion

In this paper, we conducted a six week-long RtCD study with two experienced high-school engineering teachers and collaboratively identified three specific points in engineering education where an AI system can effectively intervene to support teachers while highlighting their pedagogical approaches and experiences (i.e. AI intervention points, AI-IPs). These AI-IPs focus on documentation, ephemeral interactions between teachers and students, and disruptive failures. We discuss how AI systems can assist teachers' current practices and the importance and implications of leveraging participatory approaches in shaping the design of intelligent educational systems. By leveraging these insights, we can design intelligent educational systems that align with teachers' needs and provide them with control over computational interventions in their classrooms.

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