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Research paper

Enhancing STEM Education Through Design Thinking and Iterative Improvement in Students' Research Projects

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ABSTRACT

STEM projects are integral to STEM education, fostering critical thinking, problem-solving, and creativity. However, students often struggle with topic selection, methodology, and iterative improvement. This study investigates the integration of Design Thinking (DT) into a year-long STEM project course in a Thai high school, examining how iterative loops impact project originality and feasibility. Using a qualitative approach, data were collected through proposals, progression reports, final reports, and presentations, all of which were analysed using originality and feasibility rubrics. Results revealed that students who engaged in iterative DT processes produced more innovative and practical solutions, while those with minimal iteration faced challenges in originality and feasibility. The findings highlight the importance of structured iteration and feedback in STEM education, providing insights for educators to optimize project-based learning and support effective students in STEM projects.

Keywords: design thinking, iterative improvement, STEM education, project-based learning

STEM projects have increasingly been recognized as a vital component of secondary school education, particularly in the fields of science, technology, engineering, and mathematics (STEM). These projects aim to equip students with knowledge, skills, and attitudes essential for pursuing advanced studies and careers in STEM disciplines (Alfarraj et al., 2026; Grewe, 2025; Bennett et al., 2020; Bicer et al., 2020; Bennett et al., 2018; Balçın et al., 2018; Vossen et al., 2018; Liu et al., 2009). In Thailand, STEM projects are central to the curriculum for students enrolled in specialized science and mathematics programs, functioning as a graduation requirement. Students participated in a STEM project conducted through a Project-Based Learning (PjBL) framework. They work collaboratively to address real-world problems, fostering critical thinking and creativity (Institute for the Promotion of Teaching Science and Technology [IPST], 2009; Amka & Dalle, 2022; Danial et al., 2026).

Despite their importance, students often encounter significant challenges when completing STEM projects. These include difficulties in understanding ill-structured problems, as students often tend to settle for their first idea without sufficiently exploring alternative solutions (Christensen et al., 2019; Rusmann & Ejsing-Duun, 2022; Vossen et al., 2019). Design Thinking (DT) provides a structured, human-centered framework to address these challenges. Originating from the d.School at Stanford University, DT emphasizes five core stages: empathize, define, ideate, prototype, and test while allowing for non-linear and iterative improvement (Dam & Teo, 2025; d.school, 2018). This iterative nature of DT, often characterized by multiple loops of improvement, fosters creativity, adaptability, and resilience, making it particularly suited for STEM education.

Although DT has been widely studied, its application across different durations of STEM projects remains underexplored. Research suggests that long-term DT engagement fosters sustained positive attitudes and deeper learning outcomes, while short-term projects often generate immediate but less lasting benefits (Bennett et al., 2018; Bennett et al., 2020; Butler et al., 2023; Morrison et al., 2021; Vossen et al., 2018). However, little is known about how extended project durations influence originality, feasibility, and overall project quality when guided by DT. Few studies have examined how students iterate and refine their work overtime or how teacher feedback supports these cycles. This gap is especially relevant in Thailand, where STEM projects are mandatory in specialized science and mathematics programs (IPST, 2009). By mapping students' iterative DT processes and their associations with project outcomes, this study examines how the DT supports more effective STEM project development.

LITERATURE REVIEW

Design thinking process

DT is a human-centered approach to problem-solving that emphasizes empathy, creativity, and iterative improvement. It is particularly well-suited for addressing complex, real-world challenges, including those in education. The DT framework, as conceptualized by Stanford University's d.School, involves five iterative stages: empathize, define, ideate, prototype, and test (d.school, 2018). Each stage is designed to scaffold learners as they move from understanding user needs to developing and refining innovative solutions. Importantly, the DT process is non-linear, allowing designers to revisit earlier stages as new insights emerge (Dam & Teo, 2025; Parker et al., 2021).

Various institutions, including IDEO and the Design Council, have adapted the DT framework to emphasize its experiential and interdisciplinary nature, making it an effective tool for fostering 21st-century skills such as collaboration, critical thinking, and creativity (Chesson, 2017; Lor, 2017). DT also aligns with constructivist educational principles, encouraging students to engage in inquiry-based learning and iterative problem-solving.

STEM projects

STEM projects are increasingly employed to engage students in STEM learning by situating instruction within authentic, real-world problem contexts. Such projects commonly involve collaborative group work, enabling students to collectively apply disciplinary knowledge while developing higher-order skills. Prior research consistently indicates that project-based approaches in STEM education support students' learning in multiple and complementary ways. At the K–12 level, Markula and Aksela (2022) investigated biology-related PjBL units within nature and environment-focused science curricula. Their findings suggest that well-designed projects promote collaboration, meaningful use of technological tools, and the production of tangible artefacts, thereby supporting both cognitive and procedural aspects of learning. Extending this line of inquiry, Fang and Fan (2025) demonstrated that variations in project design led to qualitatively different learning opportunities in junior secondary classrooms. Their analysis showed that the Preliminary–Innovation projects tend to foster creativity and 21st-century competencies through discussion and presentation-based activities, whereas the Design–Build–Test projects place greater emphasis on hands-on construction, technical skills, and iterative problem-solving under constrained conditions.

At the upper secondary level, Nordlöf et al. (2024) reported that engineering design projects increased the perceived relevance of schoolwork by addressing improvements to students' physical school environments. However, their findings also reveal an imbalance in disciplinary integration, as technology and engineering dominated project activities, while science and mathematics were incorporated only at relatively superficial levels. This highlights a persistent challenge in STEM education by translating interdisciplinary intentions into enacted classroom practices that meaningfully integrate all STEM domains.

Evidence from higher education further reinforces the potential of authentic project-based learning. Beier et al. (2019) found that participation in authentic PjBL experiences positively influenced students' attitudes toward STEM and their career aspirations. Specifically, college students who engaged in at least one authentic PjBL course demonstrated significant gains in STEM career aspirations, STEM skills self-efficacy, and perceived utility value of STEM coursework. Taken together, these studies suggest that while STEM projects can effectively support engagement, skill development, and motivation across educational levels, their impact is strongly mediated by project design and the depth of disciplinary integration

STEM project under a PjBL framework in school setting

In this school setting, STEM projects are implemented within a PjBL framework that aligns closely with Thailand's national curriculum and the IPST requirements, reflecting the collaborative management of the special science and mathematics program. While the national curriculum provides mandatory guidelines, project implementation is shaped by the school context and teachers' instructional approaches. The PjBL trajectory is scaffolded across grade 11 and grade 12, beginning with a research techniques course in grade 11, Semester 1, where students develop foundational competencies in research design, data collection, and analysis. Although mathematics and scientific methodology are taught as separate subjects, students engage in authentic inquiry tasks, such as designing questionnaires, analyzing empirical data, and critically reviewing published research, culminating in assessed presentations and worksheets. Building on this foundation, STEM projects 1 in grade 11, semester 2, emphasizes collaborative, student-driven inquiry, with students working in small groups to identify real-world problems situated in scientific, mathematical, or computational contexts. This phase foregrounds literature review, iterative topic refinement, and formative feedback through regular presentations, aligning with core PjBL principles of sustained inquiry and reflection. In STEM project 2, offered in grade 12, semester 1, students advance from proposal development to project execution, analysis, and dissemination, supported by continuous teacher guidance (IPST, 2009).

Design thinking and student projects

In education, DT has been employed to support students in developing real-world solutions, especially in STEM fields. To encourage students to practice STEM and design, they often conduct STEM projects aimed at solving authentic, real-world problems. Such projects require students to apply research and design methodologies and generally work collaboratively in teams. The iterative nature of DT helps students address 'wicked problems,' or challenges without predefined solutions (Aflatoony et al., 2018; Rusmann & Ejsing-Duun, 2022). Studies have demonstrated that DT enhances students' ability to empathize with stakeholders, clearly define problems, brainstorm creative solutions, and refine prototypes (Lin et al., 2024). For example, Aflatoony et al. (2018) found that students using DT exhibited improved problem-solving skills and produced more innovative and user-centered designs.

Research by Simeon et al. (2022) highlighted the effectiveness of DT in improving STEM education outcomes, showing that students taught using the DT framework demonstrated higher achievement and retention of physics concepts compared to peers taught using traditional methods. Similarly, Lin et al. (2020) found that integrating DT into digital project work enabled students to create products that were more aligned with user needs, underscoring the value of empathy and iterative improvement in design processes.

Design thinking and duration of STEM projects

Research has shown that the duration of implementing the DT process in STEM education leads to different impacts on student learning outcomes. Long-term participation in DT-oriented programs has been associated with more positive and sustained attitudes toward research and design activities, as students engage in repeated authentic learning experiences (Bennett et al., 2018; Morrison et al., 2021; Vossen et al., 2018). In contrast, short-term, intensive interventions have been found to produce immediate gains in knowledge, skills, and self-efficacy, although these effects are often limited in sustainability (Butler et al., 2023). Thus, while both short- and long-term implementations of DT are well documented in the literature, much less is known about their influence on the originality, feasibility, and overall quality of student projects.

Moreover, few studies have examined how students engage in repeated iterative loops of improvement across extended project durations, or how these loops shape the development of research proposals and final project outcomes. Equally underexplored is the role of teachers' feedback in supporting students throughout these cycles of iteration. Addressing these gaps is essential for understanding the long-term educational value of DT in STEM education, particularly in relation to students' ability to refine and elevate the quality of their work over time.

This gap is particularly significant given the unique educational context in Thailand, where STEM projects are a mandatory component of specialized science and mathematics programs (IPST, 2009). Understanding how DT can be integrated into these programs to support students in overcoming common challenges such as topic selection, prototype development, and report writing, is critical for optimizing STEM education.

Impact of iterative loops in DT

Iterative loops, a defining feature of the DT process, play a crucial role in enhancing creativity, adaptability, and resilience (Dam & Teo, 2025). In DT, the process of design is often a non-linear process. It is a fundamental to effective design and significantly impacts student projects by fostering deeper learning, improving outcomes, and developing essential skills. This benefits students in conducting projects in different ways, such as preventing the early closure, which students often end the investigation process with their first idea or rush to a single solution (Chin et al., 2019; Vossen et al., 2019).

Prior research conceptualizes iteration as a process that can be observed and traced through learners' design actions. Marks and Chase (2019), for example, operationalized iterative loops by counting students' testing behaviors during design challenges, using the number and timing of tests as indicators of engagement with the prototyping process. By treating each test as a potential iteration, their work illustrates how iteration can be quantified as repeated cycles of action, feedback, and revision. This approach revealed that students who engaged in more frequent iterations were more likely to adopt a fail-forward mindset, characterized by productive responses to mid-task failure and active feedback seeking, ultimately leading to more successful design outcomes.

Dotson et al. (2020) identified the iterative loop as central to both student design processes and program sustainability. In this study, iteration is framed as a circular feedback loop that drives human-centered design (HCD) and supports scalable implementation. At the student level, iteration is embedded across the five HCD stages—empathize, define, ideate, prototype, and field test—enabling continuous refinement through peer and stakeholder feedback and fostering engagement and ownership through open-ended design work. Iteration is operationalized as a backward transition from prototyping to ideation or refinement. Iterative activity is measured by tracing the evolution of designs from initial sketches to optimized prototypes. Each instance in which students modify a physical prototype in response to structured feedback from peer and community panels is coded as one repetition, allowing the iterative loop in design thinking to be captured as observable and comparable design action.

Thus, students who engage in multiple iterations within DT stages are more likely to produce innovative and feasible solutions (d.school, 2018; Parker, 2021). For example, Chin et al. (2019) noted that revisiting earlier stages of DT, such as empathize and define, allows students to refine their understanding of user needs, leading to better-aligned solutions. However, the effectiveness of iterative loops depends on several factors, including the quality of teacher feedback, the availability of resources, and the students' commitment to the process (Morrison et al., 2021). To maximize the impact of DT, educators must create opportunities for students to reflect, iterate, and improve their work consistently.

METHODS

Research design

This study employed a qualitative approach to evaluate the integration of DT into a year-long STEM project course for Thai high school students.

Qualitative data were collected using evaluation rubrics, while qualitative insights were drawn from progression reports, teacher feedback, and student presentations to understand the iterative processes. A STEM project in this study is defined as a group-based learning activity managed under a PjBL framework. Unlike professional-scale research, these projects focus on the learning process where students identify problems and develop prototypes using the DT.

Students would revise their project in each step based on their further information and teacher feedback after presenting or consulting with teachers. Students wrote down teachers' feedback in progress reports and presented it before consulting. These provide the loops of repetition during the processes of conducting projects. The research aimed to assess the effectiveness of DT in improving students' final project outcomes, focusing on originality, feasibility, and overall quality

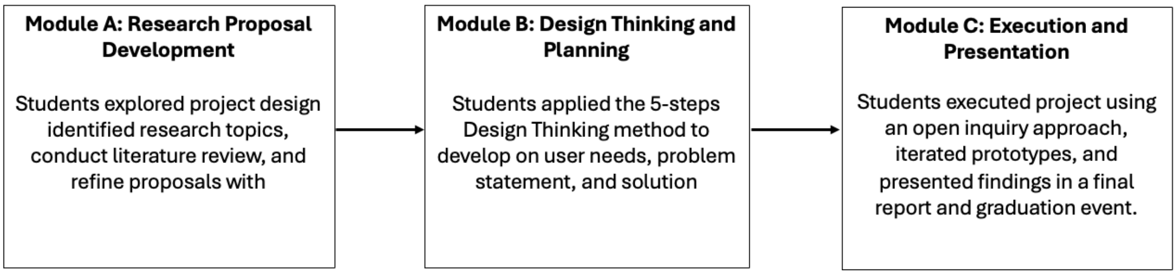
Participants

The study involved 30 high school students enrolled in a specialized science and mathematics program. These students participated in a compulsory research methods course in grade 11 and continued their projects through grade 12. Students worked in groups of 2–3, fostering collaborative problem-solving and peer learning. The participants were selected to represent a range of academic performance levels and prior research experience to ensure balanced and fair group composition. While prior knowledge and experience were not analyzed as factors affecting project outcomes, they were used to form heterogeneous teams so that each group included students with varied strengths. This approach aimed to provide equitable opportunities for collaboration and peer learning, following recommendations from previous studies on effective team formation in PjBL (Chin et al., 2019; Rusmann & Ejsing-Duun, 2022). to ensure student privacy. Participation in the study was part of the mandatory curriculum, and all data were anonymized to ensure student privacy. Ethical approval was obtained from the school administration, and informed consent was secured from both students and their guardians.

Course structure

The STEM project course was structured around the 5-step DT framework (empathize, define, ideate, prototype, and test) and divided into three modules (**Figure 1**), each targeting a distinct aspect of project development and execution. By structuring the course into these three sections, the study provided a comprehensive framework for students to develop, refine, and execute STEM projects. Each module emphasized iterative improvement, critical thinking, and creativity, equipping students with the skills needed to tackle real-world problems effectively. This modular approach also ensured students progressively built their competencies, moving from foundational understanding to advanced project execution

Figure 1
Module Summary



Module A focused on studying previous projects and understanding the principles of project design in science and mathematics. They explored various methodologies for conducting research, using literature reviews and brainstorming sessions to refine their topics. Students presented their proposals to teachers for feedback, with this process taking the entirety of grade 11. At this stage, the DT methodology was not applied, as students were focused on learning the research process and practicing topic selection. This foundational stage allowed them to develop skills in reviewing literature, analyzing prior work, and defining areas of interest, preparing them to engage in iterative DT practices later.

Module B centered on applying the 5-step DT framework as a guide for project planning and implementation. Students were introduced to the DT framework, which included the stages of empathize, define, ideate, prototype, and test, and practiced this framework through structured and guided inquiry. This module is built directly on the proposals developed in Module A. Students conducted user interviews to gather information from stakeholders, which allowed them to review and refine their initial proposals. Using insights from these interactions, they redefined problem statements (define stage), brainstormed solutions (ideate), and developed prototypes (prototype and test). This module translated students' initial proposals into actionable project plans and provided structured practice in iterative problem-solving. DT was applied starting in module B because students needed a clear topic and problem before engaging in meaningful iterative ideation and prototyping.

Module C was dedicated to project execution and final presentation. Using the refined proposals from Module B, students conducted their projects through the 5-step DT framework using an open inquiry approach. This allowed students to explore, prototype, and test solutions iteratively over the academic year. At the conclusion, students compiled their findings into a final report and presented their projects at a graduation event, showcasing both practical and innovative outcomes.

Research tools

Four primary documents were used to collect data: research proposals, final reports, progression reports, and presentations. These documents were evaluated for originality and feasibility to investigate the quality of projects using a rubric, as shown in **Table 1**. Originality and feasibility were assessed using a two-dimensional rubric, developed inductively based on how students conducted their projects, as shown in Table 1. Originality was rated on a scale from 0 to 2, where 0 indicated a repeated concept, 1 signified a modified idea with some new elements, and 2 represented an innovative and novel approach. Feasibility was assessed based on practicality and usefulness, with 2 awarded to projects meeting both criteria, 1 for those fulfilling only one, and 0 for projects lacking feasibility. The rubric was inductively developed from students' project practices and applied independently by three teachers to ensure scoring consistency. Originality was rated on a three-point scale (0–2), ranging from repeated concepts to modified ideas and novel approaches, while feasibility was evaluated based on practicality and usefulness. The results showed that originality and feasibility functioned as related but non-linear dimensions. Projects at originality level 1 primarily demonstrated adaptive application of existing ideas, with students modifying established studies, procedures, or technologies to fit local or classroom contexts while retaining core conceptual structures. Examples included contextual adjustments to experimental conditions and scaled-down applications of industrial systems. In contrast, projects rated at originality level 2 exhibited greater conceptual transformation, characterized by cross-domain integration, system redesign, and the development of new control or evaluation mechanisms. These patterns indicate distinct levels of innovation across student projects as captured by the rubric. Three independent researchers mark students' reports to ensure the validity of the scoring system on the final report.

Table 1

Rubric for evaluating the originality and feasibility of projects

Dimension	Criteria		
	0 (Needs improvement)	1 (Fair)	2 (Excellent)
Originality	The project lacks originality; copies existing ideas with no evidence of creative thinking.	The project includes some creative ideas; builds on existing solutions with moderate originality.	The project demonstrates highly creative and unique ideas; shows original thought beyond existing solutions.
Feasibility	The project is impractical; cannot be realistically implemented with given constraints.	The project has significant challenges in resources or planning; feasibility is uncertain.	The project is highly practical; implementation is realistic with available resources and clear planning.

Final research reports were assessed to measure students' ability to execute and present their projects. Progress reports tracked students' iterative improvements throughout the course alongside the integration of feedback received during the project development process. Students submitted progress in groups; these documents recorded students' presentations, consultations with teachers, and improvements at each step. Progression reports were collected after each major DT stage in DT. Feedback was provided both orally during consultations and in writing through teacher comments, allowing students to iteratively refine their projects.

DATA ANALYSIS

Data analysis combined qualitative and quantitative methods. Scores from the rubrics were analyzed to classify students into three groups based on their performance in DT stages: Complete DT (CDT), Partial DT (PDT), and Incomplete DT (IDT).

A systematic analysis of students' progress reports and final presentations revealed clear patterns in how student groups iteratively engaged with the stages of the DT process and how these patterns related to project quality. Iteration frequencies across DT stages for each group are visualised in **Figure 2**, where arrows and numerical values indicate the number of substantive revisits to each stage. These frequencies were derived from documented revisions in progress reports and progression presentations following teacher consultation and subsequent project refinement.

To operationalise iteration, all reports and presentations were coded for explicit evidence that a group revisited a DT stage in a meaningful way. Coding criteria were strictly aligned with the operational definitions of each DT stage used in this study. A repetition was recorded only when students demonstrated substantive cognitive or design revisions rather than superficial edits. For example, within the define stage, repetition was coded when students reformulated the problem statement, revised key problem definitions, or reframed user needs relative to earlier submissions. Each documented instance of such revision was counted as one repetition; thus, revising a problem definition twice across reporting cycles was coded as two repetitions. Similarly, in the prototype and test stages, repetitions were recorded when students modified prototypes based on test results, including changes to design, materials, mechanisms, or system configuration. Each documented cycle of testing followed by design modification constituted one repetition. Aggregated repetition counts per DT stage enabled cross-group comparisons and ensured that iteration reflected authentic design engagement rather than reporting frequency.

Examples of progress reports are shown in **Figures 2–4**. Final presentations provided an additional data source, allowing students to summarize their projects, respond to questions, and receive suggestions for further improvement.

To categorize levels of Design Thinking (DT) application, students' performance was analysed using established frameworks from Dam and Teo (2025) and the d.school (2018). These frameworks specify the activities, skills, and mindsets associated with each DT phase, enabling systematic identification of students' design actions. Briefly, the empathize phase involved evidence of understanding users' needs, emotions, and behaviours through interviews, surveys, observations, or literature review. The define phase captured instances of problem framing and reframing. The ideate phase focused on collaborative generation and expansion of solution ideas. The prototype phase documented the translation of ideas into tangible or digital artefacts for exploration and refinement. The test phase included evidence of evaluation against criteria or constraints, feedback collection, and reflective refinement.

Iteration was operationalised and counted through students' documented actions and behaviours recorded in progress reports and presentation materials. A thematic analysis was conducted to trace students' design trajectories over time. Three researchers independently reviewed the data to familiarise themselves with patterns of iteration, decision-making, and revision. Inductive coding captured observable iterative actions such as problem reframing, feedback integration, peer collaboration, and prototype modification. Each instance in which students revisited an earlier DT phase, particularly transitions from prototyping back to ideation, redefining, or refinement based on feedback, was coded as one iteration. These codes were subsequently clustered into broader themes representing recurring iterative patterns, including empathize–define cycling, ideation divergence and convergence, and prototype–test feedback loops. Themes were refined through researcher discussion and mapped across the CDT, PDT, and IDT groups. Notably, CDT students demonstrated sustained engagement in multiple empathize–define–ideate cycles, whereas IDT students more frequently skipped stages or exhibited surface-level iteration.

By integrating quantified iteration counts with qualitative thematic analysis, this approach offers a robust account of how students enacted DT processes. The findings indicate that meaningful iteration, evidenced through repeated cycles of reflection, redesign, and refinement, plays a critical role in supporting authentic design-based learning and shaping the quality of final project outcomes.

RESULTS

Students' project proposals and final reports were evaluated using the originality and feasibility rubric. Three groups were classified based on their scores, which reflect their varied levels of engagement with the DT, which was measured through both project products and progression documentation process, along with teachers' feedback. According to Dam & Teo, 2025 and d.School (2018) as the DT process is an iterative and non-linear process that contains five phases: 1. empathize, 2. define, 3. ideate, 4. Prototype, and 5. test. The three researchers mapped students' activities to illustrate the loops. These stages were employed to explain the student groupings.

First, students in completed DT group 1, group 2, and group 3 (CDT 1 - CDT 3) demonstrated a strong DT process with multiple loops of improvement. Students in the CDT group were thoroughly engaged in all five DT stages with multiple loops of improvement. They continuously refined their problem definitions through literature reviews, user interviews, and peer feedback, directly reflecting empathy, such as understanding users and defining phases. Their iterative nature was particularly evident in the ideate and prototype stages, where they explored multiple solutions and rigorously tested their prototypes, embodying the ideate (generating ideas), prototype (building representations), and test (evaluating solutions) phases. Their projects were both innovative and highly feasible, scoring 2 in both originality and feasibility. These students were thoroughly engaged in all DT stages, iterating frequently between problem identification, solution development, and prototype refinement.

Second, those in Partial DT group 1, group 2, and group 3 (PDT 1–3) displayed an uneven application of DT principles. Some students emphasized later DT stages (prototyping and testing) while neglecting early-stage problem definition, while others had strong initial problem-solving approaches but weaker execution in later stages. Their projects generally lacked originality or practicality, with most scoring 1 or 2 in feasibility but only 1 in originality.

Third, students classified in Incomplete DT group 1 and group 2 (IDT 1–2) had incomplete engagement in some DT steps, often progressing linearly without iterative refinement. Their projects were limited in both innovation and feasibility, with all scoring 1 in originality and feasibility. Table 2 highlights the relationship between originality and feasibility across different project groups. Which revealed distinct patterns in originality and feasibility depending on the level of engagement in the DT process. For the CDT groups, all projects achieved balanced scores of 2 in both originality and feasibility. The PDT groups showed more variation: two projects emphasized feasibility (originality = 1, feasibility = 2), while one project emphasized originality (originality = 2, feasibility = 1). In contrast, the IDT groups (n=2) consistently scored 1 in both originality and feasibility, reflecting the lowest performance across both dimensions. These results indicate a relationship between the degree of DT engagement and the ability of students to balance creativity with practicality in their projects. In sum, those in CDT consistently demonstrated both high innovation and practicality, while those in PDT and IDT showed limitations in either originality, feasibility, or both.

This study examined students' project originality and feasibility as evaluated by three teachers using a shared rubric (**Table 1**), with scores reflecting both the conceptual transformation of existing ideas and the practical viability of resulting prototypes**.** Importantly, originality and feasibility were found to be related but non-linear dimensions: projects could demonstrate high originality while remaining limited in feasibility, and vice versa.

Table 2

Summarizes the originality and feasibility ratings for each project

Project Title	Group	Originality	Feasibility
Inulin as Fat Substitute for Mayonnaise Development	CDT 1	2	2
Stainless Steel Comparison for Dental Crowns	CDT 2	2	2
Smart Farm for Controlling Salinity in Grape Seaweed Cultivation	CDT 3	2	2
Zinc Oxide and Lead Oxide Ratio for Preserving Century Eggs	PDT 1	1	2
Oil Absorption Paper from Rice Straw	PDT 2	1	2
Automatic CPR Machine for Elderly in Retirement Homes	PDT 3	2	1
Response of Mealybugs	IDT 1	1	1
CO2 Gas Capture and Removal System	IDT 2	1	1

Projects rated at originality level 1 primarily demonstrated adaptive application of existing ideas. These projects draw directly from prior studies or established technologies and modified variables, procedures, or contexts to suit local or classroom conditions. For example, the PDT 1 group adapted an existing preservation study of preservation of century egg from Chinese study by adjusting experimental conditions to reflect the Thai context, resulting in century egg products that were acceptable to users. Similarly, the IDT 2 group scaled down an industrial carbon dioxide capture system for classroom use. While these projects showed creative engagement through contextualization and practical adjustment, the core concepts remained largely unchanged, aligning with moderate originality as defined in the rubric.

In contrast, projects rated at originality level 2 exhibited deeper transformation through cross-domain application, system redesign, and the development of new control or evaluation mechanisms. The CDT 3 group, for instance, transferred IoT-based salinity sensing technology from terrestrial agriculture to marine aquaculture, informed by field observations and repeated stakeholder consultations. Likewise, the PDT 3 group redesigned CPR technology to accommodate the physical needs of elderly users in retirement homes, integrating user-centered design principles and mechanical analysis. These projects illustrate originality as a function of depth of redesign and contextual reconfiguration, rather than idea novelty alone.

Feasibility scores further differentiated projects based on prototype performance and test outcomes. Projects rated at feasibility level 1 faced substantial implementation challenges, often due to unstable or inaccurate prototype results. For example, despite high originality, the PDT 3 and IDT 3 projects produced prototypes that did not yield reliable or reproducible outcomes, limiting their applicability in real-world contexts. These findings highlight that innovative design does not guarantee practical feasibility without functional validation.

Conversely, projects rated at feasibility level 2 demonstrated consistent, accurate results and clear potential for real-world application or scale-up. The CDT 2 project produced a reliable salinity control system applicable to larger seaweed farms, while the PDT 1 project generated reproducible findings with outcomes acceptable to end users. In these cases, feasibility was supported by alignment between design intent, prototype functionality, and contextual constraints.

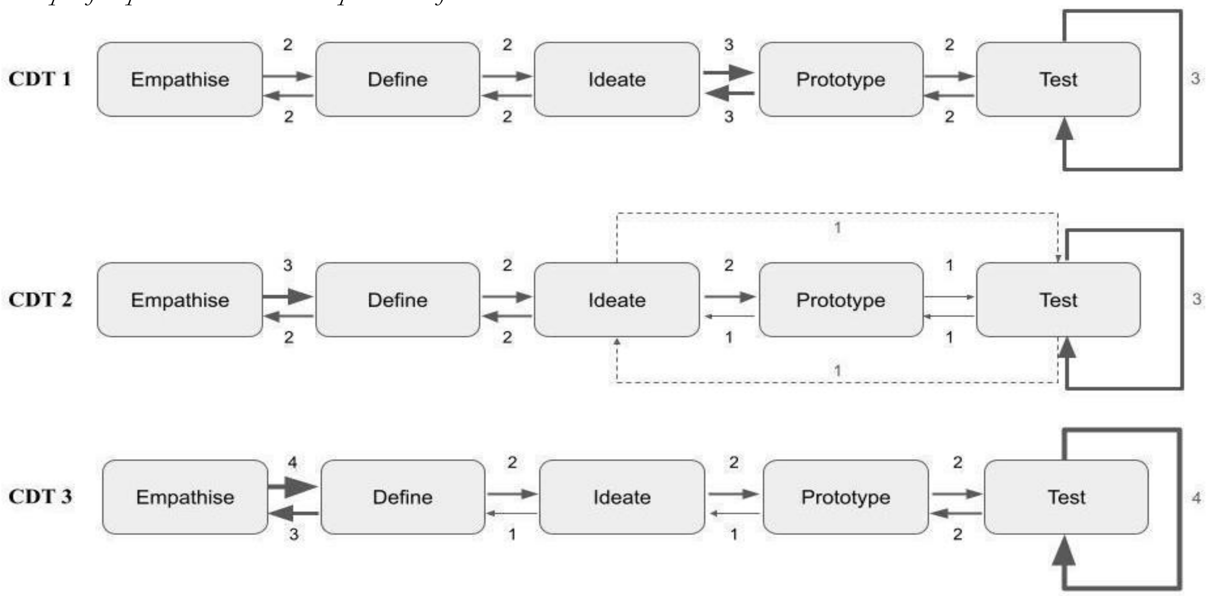
Overall, the integrated analysis suggests that high-quality STEM projects emerge from the balanced integration of originality and feasibility, where creative adaptation is accompanied by rigorous testing and realistic implementation planning. These findings underscore the value of evaluation frameworks that recognize originality as informed transformation and feasibility as evidence-based applicability, reflecting authentic STEM and design practices.

When focusing on the iterative loops of improvement following DT. The CDT groups effectively utilized all five DT stages with multiple loops of improvement, demonstrating high originality and feasibility in their projects. They continuously refined their problem definitions through literature reviews, user interviews, and peer feedback, ensuring a clear understanding of user needs. The iterative nature of their work was particularly evident in the ideate and prototype stages, where students explored multiple solutions and rigorously tested their prototypes. These loops of refinement enabled them to revisit and enhance problem definitions, solution concepts, and prototype designs based on user feedback and testing results. CDT 1 exhibited frequent iterations between the ideate, prototype, and test stages, reflecting continuous refinement of solutions.

To be clear, the repetitive pattern can be observed from documents of the CDT2 group, which studied stainless steel applications for dental crowns, illustrating how iterative DT loops were coded from progression reports and the final presentation (**Figure 2**). The group initially interviewed dentists and patients (empathize) and defined a hospital-based design problem, followed by idea generation (define–ideate). After teacher feedback, they re-engaged with users and reframed the problem toward small dental clinics, resulting in three iterations in empathize, two in define, and two in ideate. During prototyping and testing, the group identified practical constraints, including material suitability, fabrication precision, and operational feasibility in clinic settings. These issues prompted design modifications and repeated testing, leading to two ideate prototype iterations, one prototype iteration, and three test iterations. Together, these cycles demonstrate complete and meaningful iteration across all DT stages.

Meanwhile, CDT 3 emphasized user needs and solution validation through extensive back-and-forth movement between empathize, define, and test. These iterative cycles played a crucial role in fostering creativity, enhancing feasibility, and ensuring the development of well-tested, innovative final projects.

Figure 2
The loops of improvement in the DT processes of CDT 1–3.

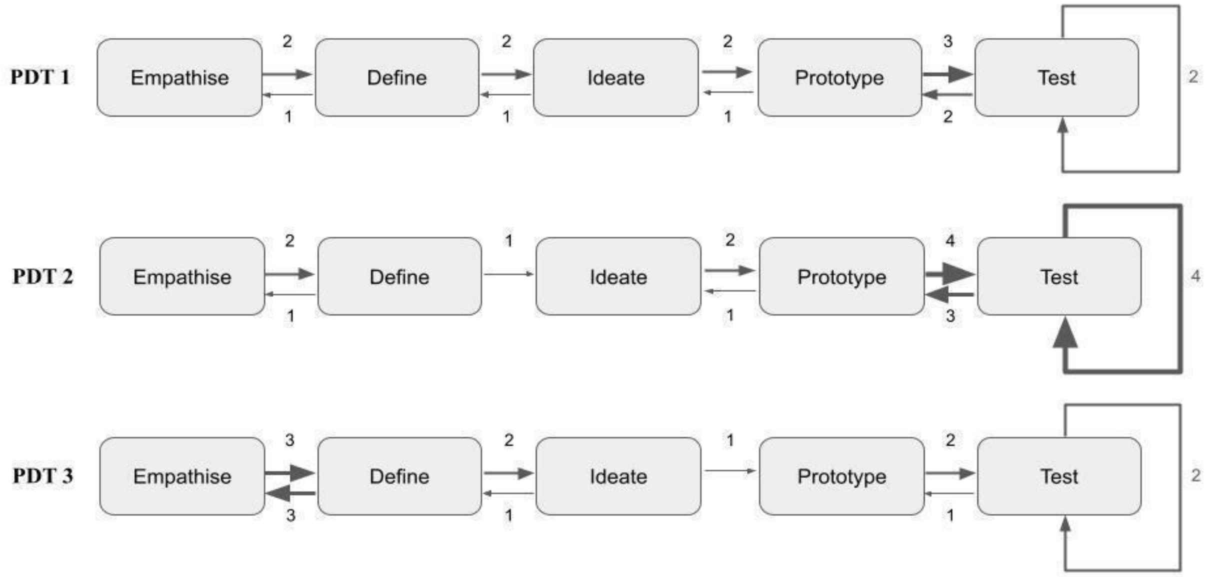


In contrast, the PDT groups were divided into two subcategories: PDT 1–2 and PDT 3. For example, the PDT 1 and 2 groups, which conduct the projects from interviewing and reviewing the existing works. They define and brainstorm for the ideas and solutions that can be applied to the context that they study. These groups started the experiment earlier than other groups because they applied the previous ideas to authentic problems that they focused on. For example, the PDT 1 reviews the elements to preserve century eggs that were used in the previous study to apply to Thai contexts. Then they conducted the experiment and test. This group revises the test and prototype many times as they rewrite in the progression report and presentation that the result from and characteristics of eggs do not belong to the characteristics that are sold in commercial ways. Thus, they backed the new ratio of elements used. Therefore, this group represents the weak in the earlier stage of DT and more rigorous in the late stages. By focusing primarily on the later phases without robust empathy and defining stages, they might have been attempting to solve problems without first spending time to determine the basic, fundamental issue or challenge assumptions. This results in solutions based on an incomplete understanding of user needs, limiting true innovation. Their projects, while highly feasible, often lacked originality as they built upon existing research with minor modifications.

As shown in **Figure 3**, PDT 1 demonstrated minimal iteration in the empathize and define stages, with more emphasis on testing, while PDT 2 displayed a slightly more balanced approach but still prioritized prototyping and testing over early-stage research. In contrast, PDT 3 students invested significant effort in the initial stages, conducting thorough literature reviews and user interviews, resulting in projects with high originality. However, their limited iteration in the prototyping and testing stages reduced the feasibility of their solutions. This suggests that while early-stage engagement fosters innovation, the lack of robust prototype testing can hinder the practical applicability of ideas.

Figure 3

The loops of improvement in the PDT processes of PDT 1–3.



Finally, the IDT students had incomplete engagement in some DT steps and often progressed linearly without iterative refinement. The group exhibited minimal iteration and incomplete implementation of the DT stages, often progressing linearly without revisiting earlier stages for refinement. This linear approach directly contradicts the fundamental description of DT as an "iterative and non-linear process". Their lack of iterative improvement resulted in projects with low originality and feasibility. As shown in Figure 4, these students primarily advanced through define, ideate, prototype, and test without substantial feedback integration or revision. While some iteration occurred between define and empathize, the overall process lacked engagement in refining problem definitions and testing solutions thoroughly. Feedback from progression reports indicated that students struggled to incorporate teacher feedback effectively, leading to project stagnation after the proposal defense stage.

For example, the IDT2 group, which developed a carbon dioxide capture system, selected both the problem and solution primarily based on existing literature. Despite conducting stakeholder interviews and receiving teacher feedback, the group largely adhered to predetermined procedures and focused heavily on prototype construction. During testing, they encountered significant limitations related to equipment constraints and scale, as reported in progression documents and the final presentation. While the project demonstrated creativity in applying existing ideas to real-world problems, the limited use of iterative loops contributed to lower originality and feasibility compared to CDT and PDT groups, underscoring the critical role of continuous iteration in effective DT practice.

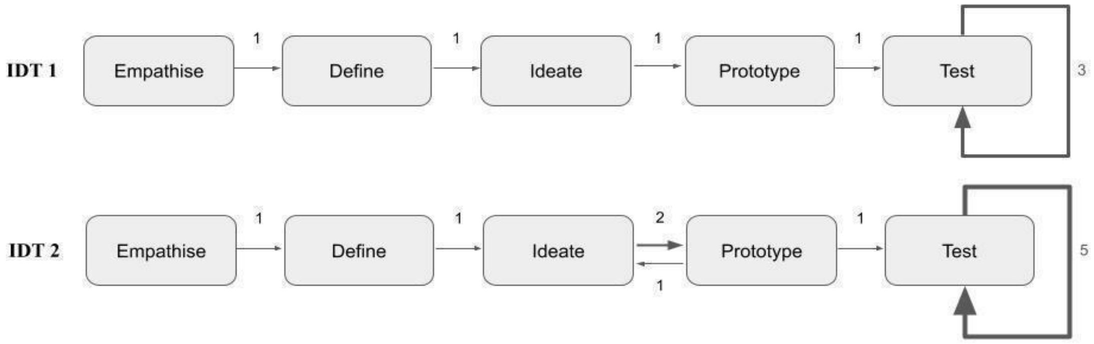
This limited use of iterative loops contributed to weaker project outcomes compared to other groups, highlighting the importance of continuous refinement in achieving innovative and feasible solutions.

To summarise the findings, the CDT, PDT, and IDT groups demonstrated varying levels of engagement with the DT process, influencing their project outcomes in originality and feasibility (Table 2). CDT students exhibited high iteration across all DT stages, ensuring continuous refinement, while PDT students showed selective repetition, with PDT 1–2 focusing on late DT stages (prototyping and testing) and PDT 3 emphasizing early DT stages (empathize, define, and ideate). IDT students followed a linear approach with minimal iteration, which limited their ability to refine ideas effectively. CDT students also engaged strongly in both early and late DT stages, balancing problem definition with prototype development. PDT 1–2 students prioritized prototyping and testing but had weaker engagement in earlier DT stages, whereas PDT 3 performed well in early stages but lacked testing. IDT students had weak engagement in both early and late DT stages, preventing meaningful project improvements.

In terms of originality and feasibility, CDT students excelled in both areas, as their iterative approach fostered innovation while ensuring practical applicability. PDT 1–2 students achieved high feasibility due to their emphasis on prototyping and testing, but their originality was limited since they primarily modified existing research. PDT 3 students demonstrated higher originality but struggled with feasibility due to limited testing. IDT students, lacking both iteration and refinement, produced projects with low originality and feasibility. These findings highlight the importance of balanced iteration and feedback integration in achieving high-quality project outcomes, with CDT students performing best, PDT groups showing strengths in select areas, and IDT students facing the greatest challenges.

Figure 4

The loops of improvement in the DT processes of IDT 1–2.



Teacher feedback and loop of repetition

The teachers' feedback had an impact on students conducting and carrying out projects. The role of teachers was to give feedback on refining project ideas to make them more feasible and original. improving experimental design, prototype development, and data collection. And enhancing report writing and presentation quality. However, the feedback would be given depending on the progression and characteristics of each student's progress each time. In this study, students in each group presented their project progression one to two times per month, following a schedule that they organized themselves. The frequency of presentations was higher during the stages of topic exploration and proposal development. In addition, each group arranged extra meetings outside of class to revise and improve their work. Consequently, the amount of feedback received by students varied across groups.

Table 3

The comparison of Iteration, Engagement, Originality, and Feasibility Among CDT, PDT, and IDT Groups

Aspect	CDT	PDT	IDT
Iteration Across DT	High repetition in all stages	Selective repetition (focus on late stages for PDT 1-2; early stages for PDT 3)	Minimal repetition
Engagement in Early DT Stages	Strong (*Empathize*, *Define*, *Ideate*)	Weak for PDT 1-2, Strong for PDT 3	Weak
Engagement in Late DT Stages	Strong (*Prototype*, *Test*)	Strong for PDT 1-2, Weak for PDT 3	Weak
Originality	High	Moderate (High for PDT 3)	Low
Feasibility	High	High for PDT 1-2, Low for PDT 3	Low

In the group CDT 1, CDT 2, and CDT 2 (CDT1-3), students consulted with peers and teachers with high frequency after getting new findings in each stage and backed projects to revise. In the PDT groups, which showed varying consulting times, PDT 1 and 2 rarely consulted in the early stages. They came up with the ideas from literature or observation from real life, then started conducting projects. However, these two groups worked hard in the late stage when they found struggles with testing prototypes and writing reports. While the PDT 3 was in contrast, this group worked harder in the early stage, which was to empathize and define problems. This group conducted interviews with users and consulted with teachers; however, after defining the problem statements, they jumped to their idea, created a prototype, and tested it with fewer refining the prototype. Finally, the IDT group, which mostly consulted with teachers but rarely applied the feedback to their processes. This group came up with single ideas and rarely changed their ideas after receiving feedback. This resulted in difficulties in the testing stage and writing final reports (**Table 3**).

DISCUSSION

The interplay between iteration and the quality of teacher feedback

The findings of this study emphasize the critical role of iterative improvement within the DT framework in fostering high-quality STEM projects. In this study, originality refers to the novelty of the students' project ideas, while feasibility indicates how practical and implementable those ideas were within the project's constraints (time, resources, and skills). Our findings suggest that these two dimensions are related but not always positively correlated, depending on how students engaged with the DT process and applied teacher feedback. Students who engaged consistently across all DT stages and revisited earlier steps when needed were classified as the Complete DT (CDT) group—produced projects with both high originality and feasibility. In contrast, Partial DT (PDT) and Incomplete DT (IDT) groups, which demonstrated selective or minimal iteration, faced limitations in achieving similarly robust outcomes.

The CDT group's success can be attributed to its consistent application of the iterative nature of DT. By revisiting the empathize and define stages, these students gained deeper insights into user needs and problem contexts, which allowed for more innovative ideation and well-aligned solutions. Their strong engagement in the prototype and test stages further ensured that their ideas were refined into practical and feasible outputs.

The PDT group presented a more fragmented approach to DT, leading to varying outcomes. PDT 1-2 students prioritized prototyping and testing but paid limited attention to earlier stages, such as empathize and define. As a result, while their projects demonstrated high feasibility, they lacked the originality seen in the CDT group. This outcome supports the notion that neglecting the foundational stages of DT can constrain creativity, as insufficient understanding of user needs and problem contexts limits the scope for innovative solutions (Lin et al., 2020). Conversely, PDT 3 students showed strong emphasis on early stages, particularly in conducting literature reviews and user interviews. This effort contributed to high originality, but their limited iteration in later stages, such as prototyping and testing, reduced the feasibility of their solutions. These findings highlight the importance of a balanced approach, where early-stage exploration is complemented by rigorous prototyping and testing.

Lastly, the IDT group, with minimal iteration and incomplete DT implementation, faced the greatest challenges. Their linear approach to project development hindered their ability to refine and adapt their work based on feedback. This resulted in projects with low originality and feasibility, underscoring the necessity of iterative loops for addressing "wicked problems" and ensuring alignment with user needs. Previous research has similarly emphasized that without consistent iteration and feedback incorporation, projects are less likely to achieve meaningful and practical outcomes (Morrison et al., 2021; Parker et al., 2021). This group mostly consulted with teachers but rarely applied the feedback to their processes. They often generated single ideas and rarely changed their ideas after receiving feedback. This could be because when teachers give feedback focusing on the project and overforcing, students think that conducting projects and writing reports are more likely to limit their willingness to fully engage in diverse research functions within a design project (Vossen et al., 2019).

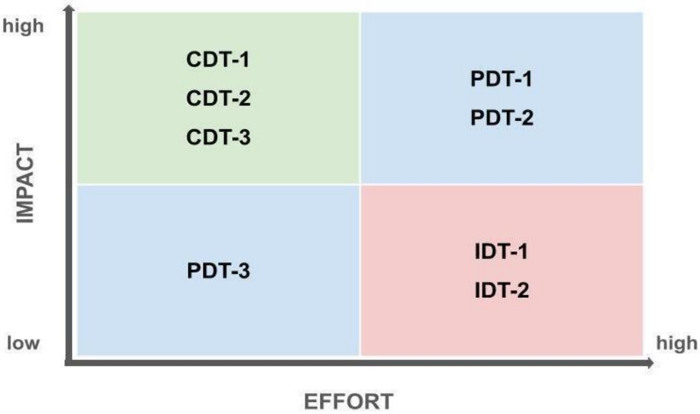
One key insight from this study is the interplay between iteration and the quality of teacher feedback. Students in the CDT group benefited from continuous feedback, which guided their iterative processes and ensured alignment with project goals. In contrast, the lack of consistent feedback loops in the PDT and IDT groups contributed to stagnation and reduced effectiveness. This finding highlights the importance of structured scaffolding and regular evaluations in supporting students through the DT process. These findings align with existing research, which suggests that iterative loops within DT not only enhance creativity but also improve the adaptability and resilience of the design process (Chin et al., 2019; Dam & Teo, 2025). Teachers often act as coaches, providing responsive guidance and advice, while peer evaluations also facilitate continuous improvement. This continuous loop of feedback and revision supports the idea of constantly reviewing, questioning, and improving initial assumptions, understandings, and results. CDT students, as a result of these iterative loops and the interpretation of previous performances, could show higher self-efficacy (Marks & Chase, 2019; Morrison et al., 2021; Vossen et al., 2019)

These results have significant implications for STEM education. First, educators should design curricula that explicitly encourage iterative improvement across all DT stages. This can be achieved by embedding structured activities that require students to revisit earlier steps. Incorporating activities that require students to revisit earlier steps, such as peer reviews, empathy exercises or brainstorming sessions, can foster deeper understanding and more innovative solutions (Butler et al., 2023; Lin, 2024). Multiple feedback cycles can also be incorporated, requiring students to present interim work during the empathy, define, ideate, and prototype stages, and revise before advancing. Second, teacher feedback should be structured to reinforce iteration, guiding students to refine their work based on new insights. Finally, providing adequate time and resources for prototyping and testing is essential, particularly for groups that demonstrate strong early-stage engagement but struggle with later-stage feasibility.

Students' performance and the Impact-Effort matrix

The success of students' final projects was influenced by several factors, including iterative loops, levels of originality and feasibility, teacher feedback, and engagement with the DT. To illustrate how these components shape student outcomes, the Impact-Effort Matrix was employed as an analytical framework, as shown in Figure 5. This matrix is widely used to evaluate innovation and service design by visualizing the balance between the effort students invested in different DT stages and the resulting impact on project quality (American Society for Quality [ASQ], 2020). Mapping the characteristics of different student groups (CDT, PDT, and IDT) onto the matrix reveals patterns in their processes and outcomes, showing how iterative improvements, feedback, and structured engagement in DT contribute to innovation and feasibility in project design (Figure 5).

Figure 5
Impact-Effort Matrix



The High Impact, Low Effort quadrant includes students who achieved significant improvements in both originality and feasibility while requiring minimal effort. The CDT 1–3 groups belong to this category, as they iterated through all DT stages with continuous teacher feedback. These students invested time in the empathize and define stages, which allowed them to frame their research questions effectively and develop well-structured procedures early in their projects. As a result, they performed efficiently in the subsequent DT stages and completed their final reports productively. This finding aligns with Vossens et al. (2019), who noted that when students dedicate time to understanding user needs and research problems while planning procedures, they are more likely to complete their projects successfully and write high-quality reports. Moreover, iterative DT loops combined with teacher feedback contributed to the high quality of their final products (Dam & Teo, 2025; d.school, 2018; Lin, 2024; Rusmann & Ejsing-Duun, 2022)

The High Impact, High Effort quadrant includes students who invested significant effort in prototyping and testing, leading to high feasibility but relatively lower originality. The PDT 1–2 groups fit this profile, as they engaged extensively in prototype development and testing, which strengthened the feasibility of their projects. However, their originality was lower because they primarily followed existing research frameworks, modifying variables or user groups rather than proposing novel ideas. Their limited engagement in the early DT stages (empathize and define) potentially restricted their ability to generate innovative solutions. Additionally, during the reporting phase, these students needed to conduct further literature reviews to justify their findings, which slightly differed from prior research. Vossen et al. (2019) support this observation, stating that students who do not engage deeply in literature reviews early on may struggle to refine their prototypes and interpret their test results effectively. Because these students adhered closely to previous research methodologies, their projects exhibited strong feasibility but lacked originality.

Students in the Low Impact, High Effort quadrant demonstrated considerable effort but lacked a strategic approach to the DT process, leading to suboptimal results in both originality and feasibility. The IDT 1–2 groups belong to this category, as they engaged with the DT framework but failed to iterate effectively. Although they attempted to progress through the DT stages, they did not revisit earlier steps when encountering challenges or receiving teacher feedback. Without consistent revision, their projects lacked meaningful or practical solutions, limiting their ability to address user needs or solve "wicked problems." Additionally, these students faced challenges in writing their final reports, often needing multiple revisions due to insufficient data to support their findings. This aligns with previous research suggesting that students who do not refine their processes through iteration struggle to produce strong final outputs (Dam & Teo, 2025; d.school, 2018; Lin et al., 2024; Marks & Chase, 2019; Rusmann & Ejsing-Duun, 2022)

The Low Impact, Low Effort quadrant includes students whose projects resulted in minimal outcomes due to inefficient iteration or misalignment with user needs. The PDT 3 group falls into this category, as they demonstrated strong originality in the early DT stages (empathize, define, ideate) but lacked sufficient engagement in prototyping and testing. Their limited prototype testing reduced project feasibility, despite their innovative ideas. Consequently, while their originality was commendable, their limited real-world applicability placed their project in the Low Impact, Low Effort category. However, their early-stage engagement in the DT process allowed them to use previously gathered insights to write their final reports more easily (Vossens et al., 2019).

Limitations and recommendations for future research

While this study highlights the benefits of DT in STEM education, certain limitations must be acknowledged. The research was conducted in a single Thai high school with a small sample size, limiting its generalizability. Future studies should explore DT's impact across diverse educational settings and larger student cohorts. Additionally, the reliance on qualitative assessments introduces potential bias; incorporating objective metrics such as learning analytics and quantitative measures could enhance accuracy.

The study focused primarily on originality and feasibility, but factors like student motivation, collaboration, and long-term skill development warrant further investigation. While DT's short-term benefits were evident, its long-term effects on academic and professional outcomes remain unclear. Longitudinal studies tracking students beyond high school could provide deeper insights. Moreover, teacher feedback played a crucial role in iteration, suggesting a need for research on structured interventions, peer feedback, and AI-driven support. Addressing these limitations will refine DT-based instructional strategies, improve student engagement, and learning outcomes in STEM education.

CONCLUSION

This study demonstrates the significant role of DT in improving STEM projects through iterative refinement, enhancing both originality and feasibility. Students who engaged consistently in all DT stages produced more innovative and well-structured solutions, while those with selective or minimal iteration encountered limitations. These findings emphasize the need for balanced iteration, structured teacher feedback, and scaffolding throughout the research process. Educators can enhance STEM education by incorporating DT principles into curricula, encouraging students to refine their work iteratively, and ensuring access to feedback mechanisms that support continuous improvement. While this study provides valuable insights, further research should explore DT's long-term impact and its applicability across diverse educational settings to maximize its benefits in fostering creativity and problem-solving skills in STEM learning.

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Ethical statement

This study adhered to ethical research guidelines, obtaining approval from the Institutional review board, Institute for Population and Social Research, Mahidol University and informed consent from students and guardians. Students were informed that participation would not affect their grades, they had the right to withdraw at any time without consequences, and their decision to use DT was voluntary. Although their proposals and final reports were used for analysis, this had no impact on their grades, as the grading process and research process were conducted separately. All data were anonymized, securely stored, and used solely for educational and research purposes. Standardized rubrics and multiple expert reviewers minimized bias in project evaluations. The study prioritized student well-being, ensuring findings were presented objectively to enhance learning experiences.

Competing interests

The authors declare no conflicts of interest associated with this study.

Author contributions

AS participated in Conceptualization, Data Collection, Data Analysis and Interpretation, and Writing – Original Draft. PY participated in Conceptualization, Data Analysis and Interpretation, Writing – Review & Editing, and Final Approval of the article. PC participated in Writing – Review & Editing and Final Approval of the article. All authors reviewed and approved the final manuscript.

Data availability

All data generated or analysed in this study are included in the article. Data were handled in accordance with applicable privacy and data protection guidelines, following best practices to ensure integrity, long-term preservation, and accessibility

AI disclosure

This manuscript utilized generative AI tools, including ChatGPT (OpenAI, 2025), exclusively to support language-related tasks such as paraphrasing, grammar checking, wording refinement, and improving clarity, as well as to assist in organizing preliminary research themes during the revision process. The AI did not contribute to the research design, data collection, data analysis, interpretation of results, or the formulation of conclusions. All academic arguments and final content were independently developed, reviewed, and verified by the author, who assumes full responsibility for the integrity and accuracy of the

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