

Research paper

Developing Creative Thinking Among Engineering Students Through STEM Technologies: A Mixed-Methods Investigation

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Citation: Baratov, D., Donayev, B., Abdimuminov, E., Nurova, O., Sharipov, S., & Rustamova, N. (2026). Developing creative thinking among engineering students through STEM technologies: A mixed-methods investigation. *European Journal of STEM Education*, 11(1), Article 56. <https://doi.org/10.20897/ejsteme/19687>

Published: October 28, 2026

ABSTRACT

Creative thinking has emerged as a critical competency in twenty-first century engineering practice, yet pedagogical strategies that systematically cultivate this capacity within STEM-oriented curricula remain underexplored. This study investigates how the purposeful integration of STEM technologies—encompassing digital fabrication tools, simulation environments, collaborative coding platforms, and project-based learning frameworks—influences the development of creative thinking skills among undergraduate engineering students. Employing a convergent mixed-methods design, the study collected quantitative data through the Torrance Tests of Creative Thinking (TTCT) administered to 124 engineering students across two cohorts at a Central Asian technical university, alongside qualitative data derived from semi-structured interviews, classroom observations, and artefact analysis conducted over one academic semester. Findings indicate statistically significant gains in creative fluency ($p < .001$, $d = 0.74$), originality ($p < .001$, $d = 0.61$), and elaboration ($p < .001$, $d = 0.58$) among students in the technology-integrated cohort relative to the comparison group. Qualitative analysis identified three enabling mechanisms: structured ambiguity in design briefs, iterative maker-cycle feedback, and cross-disciplinary technological exposure. The study contributes a theoretically grounded instructional model—the STEM Creative Cycle (SCC)—and offers practical implications for curriculum designers, faculty developers, and educational policy-makers aiming to embed creativity in engineering education.

Keywords: creative thinking, engineering education, STEM technologies, project-based learning, mixed methods, digital fabrication, undergraduate pedagogy

The accelerating pace of technological change has fundamentally redefined the competency expectations placed on graduating engineers. Employers and professional bodies increasingly foreground adaptive problem-solving, innovative ideation, and the capacity to generate novel solutions under conditions of uncertainty—competencies collectively described as creative thinking (Cropley & Cropley, 2010; National Academy of Engineering, 2004). The World Economic Forum (2023) identifies creative thinking among the fastest-growing skill demands across all industries, and engineering specifically requires professionals who can synthesise technical expertise with imaginative problem-finding and problem-solving capabilities. International frameworks for twenty-first century competences likewise position creativity as a core educational outcome (Voogt & Roblin, 2012). Yet widespread reviews of engineering curricula document a persistent gap between stated graduate attribute frameworks and actual pedagogical practice, with instructional time disproportionately devoted to the transmission of declarative

knowledge and procedural mastery at the expense of creative and higher-order cognitive processes (Crawley et al., 2014; Felder & Brent, 2016).

This tension between the demand for creative engineers and the supply of creativity-fostering pedagogies has assumed renewed urgency as nations across the global economy prioritise innovation capacity as a cornerstone of economic competitiveness. In emerging technological economies, where engineering workforce development is a strategic national priority, the need to cultivate creative thinking within technical education systems carries particular weight (President of the Republic of Uzbekistan, 2019). The transition from transmission-based to inquiry-based instructional models, however, requires not merely curricular revision but a fundamental rethinking of the role of technology, assessment, and disciplinary boundaries in engineering education.

Concurrent with this pedagogical critique, the landscape of educational technology has undergone substantial transformation. The proliferation of STEM-oriented technologies—including computer-aided design (CAD) suites, physical computing platforms such as Arduino and Raspberry Pi, computational simulation environments, digital fabrication equipment, and collaborative cloud-based coding tools—has introduced new affordances for active, inquiry-driven learning (Blikstein, 2013; Honey et al., 2014). These tools share a common characteristic: they externalise cognitive processes, making thinking visible and manipulable, and thereby create conditions conducive to iterative experimentation that is widely theorised as generative of creative cognition (Papert & Harel, 1991; Sawyer, 2012).

Despite the theoretical plausibility of this relationship, empirical investigation into the specific mechanisms through which STEM technology use promotes creative thinking in engineering contexts remains fragmented. Prior work has tended either to evaluate narrow technological interventions—a single coding platform or a standalone maker-space programme—without measuring creativity as a dependent variable (Halverson & Sheridan, 2014), or to assess creativity broadly without disaggregating the mediating role of specific technological affordances (Henriksen et al., 2017). Consequently, curriculum designers lack actionable, evidence-based guidance on how to configure STEM technology integration to reliably foster creative thinking.

The present study addresses this gap by examining a deliberately designed, semester-long instructional intervention at a technical university in Uzbekistan—a context that offers a theoretically interesting case given the country's active national agenda to transition engineering education toward innovation-driven competency models (President of the Republic of Uzbekistan, 2019). Uzbekistan's strategic emphasis on developing a knowledge-based economy has catalysed substantial investment in higher education reform, with particular attention to modernising STEM curricula to produce graduates capable of contributing to domestic innovation ecosystems. The selection of this research context thus affords both theoretical and practical significance: theoretically, it extends the predominantly Western empirical base of creativity-in-STEM research to a post-Soviet educational setting characterised by distinct institutional traditions; practically, it generates evidence directly relevant to national policy objectives.

The overarching research question is: How does purposeful integration of STEM technologies into engineering coursework affect the development of creative thinking skills among undergraduate students? This broad question is operationalised through three sub-questions:

RQ1: To what extent do students who participate in a STEM technology-integrated instructional intervention demonstrate greater gains in creative thinking—as measured by TTCT fluency, originality, and elaboration scores—than students receiving conventional instruction?

RQ2: What pedagogical mechanisms, as perceived by participants, account for observed changes in creative thinking?

RQ3: How do contextual factors—institutional culture, prior technological experience, and disciplinary identity—moderate the relationship between STEM technology use and creative development?

Each research question corresponds to a distinct strand of the mixed-methods design. RQ1 is addressed through quantitative ANCOVA of TTCT scores; RQ2 through reflexive thematic analysis of interview, observation, and portfolio data; and RQ3 through joint display integration of quantitative and qualitative findings (Creswell & Plano Clark, 2018; Guetterman et al., 2015).

The study makes three contributions. First, it provides rigorous quantitative evidence of creativity gains attributable to STEM technology integration in a non-Western engineering education context. Second, it offers a theoretically grounded qualitative account of the mechanisms underpinning these gains. Third, it synthesises these findings into the STEM Creative Cycle (SCC), a practical instructional model designed for adoption by faculty across diverse engineering programmes. By examining these questions within a Central Asian educational setting, this study also contributes much-needed cross-cultural evidence to a literature dominated by North American and European samples (e.g., Halverson & Sheridan, 2014; Scott et al., 2004).

LITERATURE REVIEW

Creative thinking in engineering education

Creativity, in the context of engineering education, is most productively understood not as an innate individual trait but as a domain-sensitive cognitive and social practice that can be cultivated through deliberate instructional conditions (Amabile, 1996; Runco, 2014). Drawing on componential models of creativity (Amabile, 1983) and systems perspectives (Csikszentmihalyi, 1999), researchers have characterised engineering creativity as involving three interacting elements: a structured domain of disciplinary knowledge; an individual's intrinsic motivation and tolerance for ambiguity; and a social field—comprising peers, mentors, and institutional norms—that evaluates and sustains creative outputs.

Empirical studies in engineering education have documented that traditional lecture-centred instruction tends to suppress creative performance by reinforcing convergent thinking patterns and penalising error (Capraro et al., 2013; Dym et al., 2005). Conversely, instructional approaches that foreground open-ended problem framing, peer collaboration, and iterative design have consistently been associated with higher scores on standardised measures of divergent thinking (Charyton & Merrill, 2009; Plucker et al., 2004). However, the operational definitions of 'creativity' and the measurement instruments employed vary substantially across studies, complicating cumulative synthesis.

Recent scholarship has further emphasised the importance of creative self-efficacy as a mediating variable in the relationship between instructional conditions and creative performance. Beghetto and Karwowski (2017) argue that students must not only possess the cognitive capacity for divergent thinking but also believe themselves capable of creative production before they will engage in creative risk-taking. This insight has important implications for the design of technology-integrated learning environments, which must attend not only to cognitive scaffolding but also to affective support. Furthermore, drawing on a mixed-methods study of science teacher education, Barak (2017) argues that twenty-first century learning environments should prepare learners to adapt to uncertain situations and should release instructional control in order to encourage exploration. Transposed to engineering education, this argument favours ill-structured problems that mirror the complexity of authentic engineering practice over decontextualised exercises with predetermined solutions.

STEM technologies as learning environments

The concept of STEM technology integration, for the purposes of this study, refers to the embedding of digital and physical computing tools, simulation platforms, and fabrication technologies as integral components of disciplinary instruction, rather than as supplementary extras appended to existing curricula (English, 2016; Honey et al., 2014). This distinction matters pedagogically: surface-level technology use—such as presenting simulations for passive viewing—is theorised to produce qualitatively different cognitive affordances than deep technology use, in which learners manipulate, programme, and iteratively redesign technological systems (Koehler & Mishra, 2009).

Constructionist learning theory (Papert & Harel, 1991) provides a foundational explanatory framework: learning is deepest when learners construct shareable artefacts through engagement with meaningful materials, and STEM technologies serve as particularly powerful materials because they provide immediate, responsive feedback on design decisions. Subsequent empirical work has confirmed that learner-directed use of physical computing and digital fabrication tools supports conceptual understanding (Blikstein, 2013), collaborative knowledge construction (Martinez & Stager, 2013), and—in studies employing divergent thinking measures—creative fluency and flexibility (Clapp et al., 2017; Sheridan et al., 2014).

Beyond constructionism, social constructivist perspectives emphasise the role of collaborative discourse in technology-mediated creativity. When learners work together on design challenges using shared technological platforms, their externalised thinking becomes subject to peer critique and refinement, generating a collective creative process that exceeds individual capability (Wells, 2000). Digital fabrication environments, in particular, appear to support this social dimension by producing tangible artefacts that serve as focal points for discussion and negotiation. Stahl et al. (2006) further argue that the interplay between individual cognition and group collaboration in computer-supported learning environments creates unique opportunities for the development of higher-order thinking skills, including creative problem-solving and critical reflection.

The empirical evidence supporting technology-enhanced creative development, while promising, remains uneven in scope and methodological rigour. Meta-analytic reviews indicate that effect sizes vary considerably depending on programme characteristics, instructional approach, and the outcome being measured (Scott et al., 2004; Tamim et al., 2011). In a second-order meta-analysis spanning four decades of research, Tamim et al. (2011) reported only a small-to-moderate average effect of technology use on learning (approximately 0.35), suggesting that the pedagogical design surrounding a technology may matter more than the technology itself. There remains

a pressing need for research that isolates the active ingredients of technology-integrated instruction and examines their differential contributions to creative thinking outcomes.

Gaps and theoretical framing

Despite the convergence of constructionist theory and preliminary empirical findings, three significant gaps remain in the literature. First, most studies have been conducted in informal learning settings—after-school maker-spaces, summer camps, museum workshops—with limited translation to formal higher education engineering programmes (Martin, 2015). Second, creativity is rarely treated as the primary dependent variable; more commonly it appears as a secondary outcome subordinate to content knowledge or technical skill acquisition. Third, the mechanisms through which specific technological affordances produce creative outcomes remain theoretically underspecified, with most accounts relying on general constructionist principles rather than granular analysis of learner experience.

The present study addresses these gaps by positioning creative thinking as the primary outcome variable, locating the intervention in a formal undergraduate engineering programme, and using convergent mixed methods to generate both outcome evidence and mechanistic explanation. Theoretically, the study draws on Sawyer's (2012) improvisation model of creative learning—which foregrounds the generative tension between constraint and freedom—alongside Zimmerman's (2002) self-regulated learning framework, which helps account for the role of metacognitive monitoring in iterative design processes. The combination of these frameworks allows for a nuanced understanding of how technological tools, when embedded in carefully designed pedagogical structures, can systematically develop creative competencies in engineering students.

METHOD

Research design

This study employed a convergent parallel mixed-methods design (Creswell & Plano Clark, 2018), in which quantitative and qualitative strands were conducted simultaneously and with equal priority, and merged at the interpretation stage. This design was chosen because neither strand alone could answer all three research questions: quantitative data were necessary to establish the magnitude and significance of creativity gains, while qualitative data were necessary to illuminate underlying mechanisms and contextual moderators. Institutional ethical approval was obtained prior to data collection, and all participants provided written informed consent in accordance with the Declaration of Helsinki principles.

Participants and setting

Participants were 124 second-year undergraduate students enrolled in two parallel sections of a required course titled Engineering Design Fundamentals at a technical university in Uzbekistan. The intervention cohort ($n = 63$; 41 male, 22 female; mean age = 19.4 years, $SD = 0.87$) was taught using the STEM technology-integrated approach described below. The comparison cohort ($n = 61$; 39 male, 22 female; mean age = 19.6 years, $SD = 0.91$) received conventional instruction based on the standard course syllabus, which emphasised textbook-based problem sets, instructor demonstrations, and laboratory sessions with prescribed procedures. Both cohorts were taught by the same instructor to control for teacher effects, and assignment to cohort followed the university's existing timetabling schedule, which was independent of student characteristics, yielding a non-randomised comparison-group design embedded within the convergent mixed-methods framework (Creswell & Plano Clark, 2018). Pre-intervention equivalence on TTCT scores was confirmed (see Results).

All participants were enrolled in the Mechanical Engineering or Mechatronics programmes and had completed one year of foundational coursework in mathematics, physics, and introductory engineering principles. Students with prior experience in maker-space or fabrication environments were not excluded, as the study aimed to reflect the diversity of the student population; however, prior experience was recorded and included as a covariate in supplementary analyses, which confirmed that it did not significantly influence the pattern of results. The relatively homogeneous demographic composition of the sample reflects the gender distribution typical of engineering programmes in the region, where female enrolment in technical disciplines, while growing, remains below parity.

Intervention description

The STEM technology-integrated intervention was designed across 16 weeks and organised around four iterative design cycles of four weeks each. Each cycle presented students with a progressively more complex, open-ended engineering challenge situated in a socially relevant context (e.g., sustainable urban mobility; accessible assistive technology). Within each cycle, students were expected to define the problem, generate multiple conceptual solutions, prototype using available technologies, test and receive feedback, and refine their designs,

reflecting established models of the engineering design process (Design Council, 2019; Dym et al., 2005). The STEM technology repertoire available to students included CAD software (Autodesk Fusion 360), Arduino-based physical computing kits, 3D printers, laser cutters, and Python-based data analysis environments, consistent with the tool repertoires described in the digital fabrication and maker literature (Blikstein, 2013; Martinez & Stager, 2013). Crucially, students were free to select which technologies to employ for each challenge, fostering agentic decision-making (Clapp et al., 2017).

Three design principles guided the intervention. First, structured ambiguity: design briefs were intentionally under-specified to require students to define success criteria, thereby activating divergent thinking (Sawyer, 2012). Second, iterative maker cycles: assessment was attached to the quality of iteration documentation rather than final artefact quality, reinforcing the value of productive failure (Martin, 2015; Papert & Harel, 1991). Third, cross-disciplinary technological exposure: each cycle deliberately introduced a technology from a discipline adjacent to the students' primary specialisation, requiring conceptual transfer (English, 2016). These principles were operationalised through detailed rubrics that made explicit the creative process skills being assessed, ensuring that students understood the instructional emphasis on thinking processes rather than final products (Felder & Brent, 2016).

Measures

Creative thinking was assessed using the Figural Form A of the Torrance Tests of Creative Thinking (TTCT; Kim, 2006; Torrance, 1966), which provides norm-referenced scores for five dimensions: fluency, originality, elaboration, abstractness of titles, and resistance to premature closure. For the purposes of this study, the primary dependent variables were fluency, originality, and elaboration, as these most directly map onto the theoretical dimensions emphasised in engineering design creativity literature (Charyton & Merrill, 2009). TTCT was administered at the beginning (T1) and end (T2) of the semester by trained assessors blind to cohort assignment. The TTCT has demonstrated strong reliability in adult samples (Cronbach's $\alpha = .88-.92$ across dimensions; Kim, 2006) and has been validated for use in non-English-speaking contexts (Bart et al., 2017).

Qualitative data collection

Qualitative data were collected through three complementary methods. First, semi-structured interviews of 45–60 minutes were conducted with 24 purposively selected students from the intervention cohort at the end of the semester, stratified by TTCT gain score (high, medium, low) and gender, following purposive sampling procedures for mixed-methods research (Creswell & Plano Clark, 2018). Interviews were audio-recorded and transcribed verbatim. Second, six classroom observations of 90-minute duration were conducted at key junctures in the design cycles, with field notes recorded using a structured observation protocol. Third, student design portfolios—containing sketches, CAD files, iteration logs, and reflective journal entries—were collected for artefact analysis, an approach used in comparative research on learning in makerspaces (Sheridan et al., 2014).

Data analysis

Quantitative analysis employed analysis of covariance (ANCOVA), with T2 TTCT subscale scores as dependent variables, cohort as the independent variable, and T1 TTCT subscale scores as covariates, controlling for pre-existing differences. Effect sizes were computed as Cohen's d . Statistical analyses were conducted in R (version 4.3.1; R Core Team, 2023).

Qualitative data were analysed using reflexive thematic analysis (Braun & Clarke, 2022), proceeding through familiarisation, initial coding, theme development, review, and definition. Analysis was conducted in NVivo 14. Trustworthiness was established through member-checking with eight interview participants, negative case analysis, and inter-rater reliability coding of 20% of interview transcripts (Cohen's $\kappa = .81$).

Quantitative and qualitative findings were merged through a joint display analysis (Guetterman et al., 2015), in which quantitative outcomes and qualitative themes were mapped against each other to identify convergence, divergence, and explanatory elaboration.

RESULTS

Pre-intervention equivalence

ANCOVA assumptions were checked and met. Levene's test confirmed homogeneity of variance for all three subscales ($p > .05$). Pre-intervention TTCT scores did not differ significantly between cohorts: fluency ($t(122) = 0.43$, $p = .67$), originality ($t(122) = 0.71$, $p = .48$), elaboration ($t(122) = 0.29$, $p = .77$), confirming baseline equivalence.

Quantitative findings: TTCT outcomes

Table 1 presents adjusted post-test means and ANCOVA results for the three TTCT subscales.

Table 1

Adjusted Post-Test TTCT Scores and ANCOVA Results by Cohort

TTCT subscale	Intervention <i>M</i> (<i>SD</i>)	Comparison <i>M</i> (<i>SD</i>)	<i>F</i> (1, 121)	<i>p</i>	Cohen's <i>d</i>
Fluency	28.4 (4.1)	23.7 (4.6)	34.2	< .001	0.74
Originality	19.6 (3.8)	16.2 (3.9)	22.1	< .001	0.61
Elaboration	22.1 (4.3)	18.9 (4.5)	19.4	< .001	0.58

Note. *N* = 124 (intervention *n* = 63; comparison *n* = 61). Means are ANCOVA-adjusted post-test (T2) scores with pre-test (T1) scores entered as the covariate. Effect sizes are Cohen's *d*.

The intervention cohort demonstrated significantly higher adjusted post-test scores on all three TTCT subscales. Effect sizes ranged from medium to large ($d = 0.58\text{--}0.74$), with fluency showing the strongest effect. Examining within-cohort gain scores further revealed that intervention students showed mean gains of 6.2, 4.1, and 4.8 points on fluency, originality, and elaboration respectively, compared with mean gains of 1.3, 0.9, and 1.1 points in the comparison cohort.

Qualitative findings: Mechanisms of creative development

Reflexive thematic analysis (Braun & Clarke, 2022) of interview transcripts, observation notes, and portfolio artefacts yielded three overarching themes accounting for the creative gains observed in the intervention cohort.

Theme 1: Structured ambiguity as a catalyst for divergent thinking

Participants consistently identified the open-ended character of design briefs as a catalyst for generating multiple, diverse ideas. Students reported that when problems were under-specified, they were compelled to engage in what one participant described as 'thinking from many angles at once.' Observation notes confirmed that during early-cycle ideation sessions, intervention students produced noticeably more solution sketches per unit time than were typically observed in conventional laboratory sessions; this observation is descriptive and was not tested statistically. Portfolio analysis revealed that high-gain students, in particular, documented a wider range of conceptual directions before committing to a design path, consistent with theoretical accounts of exploratory ideation (Runco, 2014; Sawyer, 2012).

Theme 2: Iterative maker cycles as scaffolds for elaborative thinking

The iterative structure of the design cycles—particularly the requirement to document and reflect on each iteration—was identified by participants as transformative in how they approached refinement. Students described developing what might be characterised as a 'productive relationship with failure,' in which an unsuccessful prototype was reframed as generative rather than terminal, echoing constructionist accounts of learning through iterative making (Martin, 2015; Papert & Harel, 1991) and the monitoring and adapting phases of self-regulated learning (Zimmerman, 2002). Notably, elaboration gains on the TTCT were most pronounced among students whose portfolios contained the highest number of documented iteration cycles ($r = .51$, $p < .001$, $n = 63$), suggesting a dose-response relationship between iterative engagement and elaborative thinking.

Theme 3: Cross-disciplinary technological exposure and conceptual transfer

The deliberate introduction of technologies from adjacent disciplines—for example, requiring mechanical engineering students to engage with biologically inspired design principles through parametric CAD tools—was identified as generating what participants described as 'thinking in ways I had never considered before.' This cross-disciplinary exposure appeared to function by disrupting habitual solution schemas, prompting analogical reasoning and the importation of concepts from unfamiliar domains, a process widely regarded as central to creative cognition (Sawyer, 2012) and to integrated STEM learning (English, 2016). Observation data corroborated this mechanism: the most creative solutions documented in student portfolios consistently drew on cross-domain analogies introduced through the technology exposure activities.

Mixed-methods integration: Joint display analysis

Joint display analysis (Guetterman et al., 2015) revealed strong convergence between quantitative outcomes and qualitative mechanisms. The magnitude of TTCT fluency gains corresponded to the qualitative theme of structured

ambiguity: high-fluency gainers described more extensive engagement with open-ended ideation. TTCT elaboration gains corresponded to the iterative maker cycle theme: high-elaboration gainers demonstrated significantly more iteration cycles in their portfolios. TTCT originality gains, while somewhat more diffuse, corresponded most closely to cross-disciplinary exposure, with the most original solutions (as rated by blind external judges on a domain-appropriate originality rubric) disproportionately featuring cross-domain conceptual transfers.

One area of divergence concerned gender. In interviews, female students in the intervention cohort more frequently described intrinsic motivation and growing confidence in their creative abilities than male peers, yet quantitative TTCT gains did not differ significantly by gender. Qualitative analysis suggested that female students may have been engaging more deeply in reflective elaboration—a process that contributed to equivalent quantitative gains despite describing lower initial confidence in their creative abilities. Because creative self-efficacy was not measured with a standardised instrument, this interpretation should be regarded as tentative. Creative self-beliefs and creative performance are, moreover, theorised as distinct constructs (Beghetto & Karwowski, 2017).

DISCUSSION

Interpretation of findings

This study provides convergent mixed-methods evidence that purposeful integration of STEM technologies within engineering coursework produces significant and practically meaningful gains in creative thinking, as measured by internationally validated TTCT subscales. The effect sizes obtained ($d = 0.58\text{--}0.74$) compare favourably with meta-analytic benchmarks for creativity-focused educational interventions (Scott et al., 2004, report an overall effect of approximately 0.68) and exceed the average effect of approximately 0.35 reported for technology use in general (Tamim et al., 2011), underscoring the importance of instructional intentionality. Because these benchmarks were derived from different outcome measures, the comparison should be read as indicative rather than direct.

The three mechanisms identified through qualitative analysis—structured ambiguity, iterative maker cycles, and cross-disciplinary exposure—contribute theoretical specificity to the largely underspecified constructionist account of technology-creativity linkages in the prior literature. Structured ambiguity operationalises, within an engineering curriculum context, Sawyer's (2012) proposition that creative learning requires generative tension between constraint and freedom: briefs were sufficiently structured to provide disciplinary direction but sufficiently open to require divergent ideation. The iterative maker cycle mechanism resonates with Zimmerman's (2002) self-regulated learning model, particularly the monitoring and adapting phases, and extends it by demonstrating that these processes are not merely academic self-regulation strategies but creativity-generative practices when enacted through technology-mediated design.

The STEM creative cycle (SCC) model

Synthesising quantitative findings and qualitative mechanisms, this study proposes the STEM Creative Cycle (SCC) as a theoretically grounded instructional model for engineering faculty, drawing on constructionist (Papert & Harel, 1991), creative-learning (Sawyer, 2012), and self-regulated learning (Zimmerman, 2002) perspectives. The SCC comprises four phases, designed to be iterated across a semester:

Phase 1—Frame: Present an open-ended, socially situated problem with intentional under-specification, activating divergent thinking and intrinsic motivation (Amabile, 1996; Runco, 2014).

Phase 2—Explore: Facilitate cross-disciplinary technological exposure through curated materials and cross-domain analogies, destabilising habitual solution schemas (English, 2016; Sawyer, 2012).

Phase 3—Make: Support technology-mediated prototyping with an explicit iteration mandate; assess iteration quality rather than final output quality (Blikstein, 2013; Martin, 2015).

Phase 4—Reflect: Require structured metacognitive reflection on the creative process—specifically on what constraints were productively broken, what analogies were generated, and what was learned through failure (Zimmerman, 2002).

The SCC is not presented as a rigid linear sequence but as a cyclical and recursive framework in which Phase 4 reflection feeds back into Phase 1 re-framing in subsequent cycles. The model is compatible with existing engineering design process frameworks (e.g., the Double Diamond; Design Council, 2019) and can be adapted for deployment within a range of technology repertoires.

Faculty adopting the SCC are encouraged to view the phases as flexible guidelines rather than prescriptive rules, adapting implementation to their specific disciplinary context and available resources (Koehler & Mishra, 2009).

Contextual considerations

The Uzbekistan setting merits explicit discussion. The university context is characterised by strong institutional hierarchies, exam-focused assessment traditions, and relatively recent engagement with maker-space pedagogy, features that national reform policy explicitly seeks to change through a shift from theory-oriented curricula towards practical skill development (President of the Republic of Uzbekistan, 2019)—features that might be expected to moderate or suppress the creative effects of the intervention. The fact that significant effects were nonetheless obtained suggests that the design principles underpinning the intervention, subsequently synthesised as the SCC, can generate creative gains even in institutionally conservative contexts, provided that faculty implement the core mechanisms with fidelity. This finding has implications for practitioners in comparable educational systems across Central and South Asia, the Middle East, and other regions undergoing engineering curriculum reform. Although the SCC itself has yet to be tested as a stand-alone model, the present results suggest that creativity-oriented pedagogical innovation need not await wholesale institutional transformation; rather, committed faculty working within existing curricular structures can effect meaningful change through principled instructional design.

Implications for practice

The findings of this study carry several practical implications for engineering educators and curriculum designers. First, the SCC model provides a ready-to-implement framework that can be adapted across different engineering disciplines and institutional contexts. Faculty seeking to develop creative thinking in their students need not abandon existing curricula; rather, they can embed the four SCC phases within existing design or project-based courses (Capraro et al., 2013; Crawley et al., 2014).

Second, the study highlights the importance of assessment alignment. When creativity is valued but only final products are assessed, students rationally optimise for product quality at the expense of creative exploration (Amabile, 1996). The intervention's emphasis on documenting iterative process—rather than evaluating final artefacts—represents a concrete strategy for aligning assessment with creative learning goals (Felder & Brent, 2016).

Third, the cross-disciplinary exposure mechanism suggests that creativity development benefits from curricular structures that deliberately disrupt disciplinary silos (English, 2016; Honey et al., 2014). Engineering programmes might consider inter-departmental collaborations in which students encounter technologies and design traditions from fields outside their primary specialisation. Such exposure need not be extensive; even brief, structured encounters with unfamiliar technologies appear sufficient to trigger conceptual transfer.

Finally, the findings suggest that investment in physical maker infrastructure—while necessary—is insufficient without concomitant attention to pedagogical design. Universities that purchase 3D printers and Arduino kits without reconsidering assessment structures, problem framing, and cross-disciplinary linkages risk deploying expensive equipment in service of conventional, convergent instructional practices (Halverson & Sheridan, 2014; Tamim et al., 2011). The SCC model offers a coherent framework for ensuring that technological resources are deployed in ways that genuinely support creative development.

Limitations

Several limitations constrain the generalisability of these findings. First, random assignment to cohort was not possible; while pre-test equivalence was confirmed, unobserved confounders cannot be entirely excluded. Second, the intervention was taught by a single instructor, limiting control over implementation fidelity and generalisability across teaching styles; moreover, the instructor was aware of which section received the intervention, which may have introduced expectancy effects. Third, TTCT Figural Form A measures general creative potential rather than domain-specific engineering creativity (Kim, 2006); future research should complement TTCT with discipline-specific creativity assessments (e.g., Charyton & Merrill, 2009). Fourth, the study was conducted over a single semester; longitudinal follow-up is needed to assess whether creative gains persist and transfer to authentic engineering contexts. Fifth, the sample was drawn from a single institution; multi-site replication is warranted before broad generalisations are made.

Additionally, the reliance on self-report data for qualitative mechanisms introduces the possibility of social desirability bias, particularly given that interviews were conducted by a research team member associated with the course. While member-checking and negative case analysis (Creswell & Plano Clark, 2018) were employed to enhance credibility, independent replication with third-party evaluators would strengthen confidence in the identified mechanisms. The absence of a delayed post-test also precludes conclusions about the durability of creative thinking gains over extended periods. Finally, creative self-efficacy and motivation were inferred from interview data rather than measured with validated scales; future studies should include standardised self-report instruments alongside performance-based creativity measures.

A further limitation concerns the generalisability of the SCC model to resource-constrained institutions. While the intervention was implemented at a university with established maker-space facilities, many engineering programmes—particularly in developing economies—lack comparable infrastructure. The extent to which the SCC phases can be enacted with lower-cost technological alternatives (Blikstein, 2013) represents an important avenue for future investigation.

CONCLUSION

This study has demonstrated that purposeful integration of STEM technologies—guided by principles of structured ambiguity, iterative maker cycles, and cross-disciplinary exposure—produces significant and practically meaningful gains in creative thinking among undergraduate engineering students. Using a convergent mixed-methods design, the study established both the magnitude of these gains and the mechanisms through which they are generated, contributing the STEM Creative Cycle (SCC) as an evidence-based instructional model for engineering faculty.

The findings carry implications for three audiences. For curriculum designers, they demonstrate that creativity development need not be treated as a separate add-on module but can be embedded within existing engineering courses through deliberate redesign of pedagogical frameworks and technology deployment (Crawley et al., 2014). For faculty developers, they highlight specific mechanisms—ambiguity, iteration, and cross-disciplinary exposure—that can be emphasised in professional development programmes. For educational policy-makers, particularly those engaged in reforming engineering education in emerging technological economies, they provide evidence that creativity-oriented instructional innovation is viable and effective even within constrained institutional contexts (President of the Republic of Uzbekistan, 2019).

Future research should extend this work through longitudinal designs that track the persistence of creative gains; multi-site studies that test the SCC's generalisability across national and disciplinary contexts; and experimental designs with random assignment that would strengthen causal inference (Creswell & Plano Clark, 2018). Researchers should also explore the role of teacher beliefs and professional identity in moderating the implementation fidelity of creativity-oriented STEM interventions (Koehler & Mishra, 2009), an issue that the present single-instructor design could not address.

Additionally, the growing availability of generative artificial intelligence tools presents both opportunities and challenges for creativity-oriented engineering education. Future investigations might examine how AI-assisted design tools interact with the SCC phases—particularly the Explore and Make phases—and whether their integration amplifies or attenuates the creative thinking gains documented in this study. Understanding the conditions under which AI augments rather than replaces human creative agency will be essential for the continued evolution of evidence-based engineering pedagogy in an era of rapid technological change.

In summary, this study contributes to the growing body of evidence demonstrating that creative thinking in engineering education can be systematically developed through intentional pedagogical design. The STEM Creative Cycle provides a practical, evidence-informed framework for educators seeking to cultivate the creative capacities that twenty-first century engineering practice demands.

Acknowledgement

The authors thank the second-year Mechanical Engineering and Mechatronics students of Karshi State Technical University who participated in this study. The authors are also grateful to the trained assessors who administered and scored the Torrance Tests of Creative Thinking, to the external judges who rated the originality of student design solutions, and to the administration of Karshi State Technical University for providing access to the maker-space and digital fabrication facilities used in the intervention.

Funding

This research received no external funding.

Ethical statement

This study was conducted in accordance with the ethical principles of the Declaration of Helsinki. Ethical approval was obtained from the Ethics Committee of Karshi State Technical University (approval No. UTF-01) prior to data collection. Participation was voluntary; all participants were informed about the aims and procedures of the study, were assured that participation or non-participation would not affect their course grades, could withdraw at any time without penalty, and provided written informed consent. All data were anonymised before analysis and stored securely, with access restricted to the research team.

Competing interests

The authors declare that they have no competing interests.

Author contributions

D.B.: research concept and design; data collection and assembly; data analysis and interpretation; writing the article; critical revision of the article; and final approval of the article. B.D.: collection and assembly of data. E.A.: data analysis and interpretation. O.N.: writing the article and final approval. S.S.: critical revision of the article. N.R.: research concept and design. All authors have read and approved the final version of the manuscript and agreed to its publication.

Data availability

The anonymised quantitative data (TTCT scores) that support the findings of this study are available from the corresponding author upon reasonable request. Interview transcripts, observation notes and student portfolios are not publicly available in order to protect participant confidentiality, in line with the informed consent obtained from participants.

AI disclosure

The authors acknowledge the use of Claude (Anthropic, version claude-sonnet-4-20250514) to assist in structuring and language polishing of this manuscript. The following prompts were used: “Review this methodology section for clarity and APA 7 compliance” and “Check transitions between sections.” During the revision stage, Claude (Anthropic) was additionally used to check the agreement between in-text citations and the reference list and to polish the language. At the production stage, Claude (Anthropic) was used to format the accepted manuscript according to the journal template and to check the reference list against APA 7th edition style and DOI availability. Claude was not used to generate data, conduct analysis, create figures or fabricate references. All intellectual content, research design, data collection, analysis, interpretation, and conclusions are entirely the authors’ own, and all reference corrections were verified by the authors against the original sources. The authors take full responsibility for the content of this article.

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REFERENCES

- Amabile, T. M. (1983). The social psychology of creativity: A componential conceptualization. *Journal of Personality and Social Psychology*, 45(2), 357–376. <https://doi.org/10.1037/0022-3514.45.2.357>
- Amabile, T. M. (1996). *Creativity in context: Update to the social psychology of creativity*. Westview Press. <https://doi.org/10.4324/9780429501234>
- Barak, M. (2017). Science teacher education in the twenty-first century: A pedagogical framework for technology-integrated social constructivism. *Research in Science Education*, 47(2), 283–303. <https://doi.org/10.1007/s11165-015-9501-y>
- Bart, W. M., Hokanson, B., & Can, İ. (2017). An investigation of the factor structure of the Torrance Tests of Creative Thinking. *Educational Sciences: Theory & Practice*, 17(2), 515–528. <https://doi.org/10.12738/estp.2017.2.0051>
- Beghetto, R. A., & Karwowski, M. (2017). Toward untangling creative self-beliefs. In M. Karwowski & J. C. Kaufman (Eds.), *The creative self: Effect of beliefs, self-efficacy, mindset, and identity* (pp. 3–22). Academic Press. <https://doi.org/10.1016/B978-0-12-809790-8.00001-7>
- Blikstein, P. (2013). Digital fabrication and ‘making’ in education: The democratization of invention. In J. Walter-Herrmann & C. Büching (Eds.), *FabLabs: Of machines, makers and inventors* (pp. 203–222). transcript Verlag. <https://doi.org/10.1515/transcript.9783839423820.203>
- Braun, V., & Clarke, V. (2022). *Thematic analysis: A practical guide*. SAGE.
- Capraro, R. M., Capraro, M. M., & Morgan, J. R. (Eds.). (2013). *STEM project-based learning: An integrated science, technology, engineering, and mathematics (STEM) approach* (2nd ed.). Sense Publishers. <https://doi.org/10.1007/978-94-6209-143-6>
- Charyton, C., & Merrill, J. A. (2009). Assessing general creativity and creative engineering design in first year engineering students. *Journal of Engineering Education*, 98(2), 145–156. <https://doi.org/10.1002/j.2168-9830.2009.tb01013.x>
- Clapp, E. P., Ross, J., Ryan, J. O., & Tishman, S. (2017). *Maker-centered learning: Empowering young people to shape their worlds*. Jossey-Bass.
- Crawley, E. F., Malmqvist, J., Östlund, S., Brodeur, D. R., & Edström, K. (2014). *Rethinking engineering education: The CDIO approach* (2nd ed.). Springer. <https://doi.org/10.1007/978-3-319-05561-9>
- Creswell, J. W., & Plano Clark, V. L. (2018). *Designing and conducting mixed methods research* (3rd ed.). SAGE.
- Cropley, D. H., & Cropley, A. J. (2010). Functional creativity: “Products” and the generation of effective novelty. In J. C. Kaufman & R. J. Sternberg (Eds.), *The Cambridge handbook of creativity* (pp. 301–318). Cambridge University Press. <https://doi.org/10.1017/CBO9780511763205.019>
- Csikszentmihalyi, M. (1999). Implications of a systems perspective for the study of creativity. In R. J. Sternberg (Ed.), *Handbook of creativity* (pp. 313–336). Cambridge University Press. <https://doi.org/10.1017/CBO9780511807916.018>
- Design Council. (2019). *What is the framework for innovation? Design Council's evolved Double Diamond*. <https://www.designcouncil.org.uk/our-resources/framework-for-innovation/>
- Dym, C. L., Agogino, A. M., Eris, O., Frey, D. D., & Leifer, L. J. (2005). Engineering design thinking, teaching, and learning. *Journal of Engineering Education*, 94(1), 103–120. <https://doi.org/10.1002/j.2168-9830.2005.tb00832.x>
- English, L. D. (2016). STEM education K–12: Perspectives on integration. *International Journal of STEM Education*, 3(1), Article 3. <https://doi.org/10.1186/s40594-016-0036-1>
- Felder, R. M., & Brent, R. (2016). *Teaching and learning STEM: A practical guide*. Jossey-Bass.
- Guetterman, T. C., Feters, M. D., & Creswell, J. W. (2015). Integrating quantitative and qualitative results in health science mixed methods research through joint displays. *Annals of Family Medicine*, 13(6), 554–561. <https://doi.org/10.1370/afm.1865>
- Halverson, E. R., & Sheridan, K. M. (2014). The maker movement in education. *Harvard Educational Review*, 84(4), 495–504. <https://doi.org/10.17763/haer.84.4.34j1105427t516m4>
- Henriksen, D., Richardson, C., & Mehta, R. (2017). Design thinking: A creative approach to educational problems of practice. *Thinking Skills and Creativity*, 26, 140–153. <https://doi.org/10.1016/j.tsc.2017.10.001>

- Honey, M., Pearson, G., & Schweingruber, H. (Eds.). (2014). *STEM integration in K–12 education: Status, prospects, and an agenda for research*. National Academies Press. <https://doi.org/10.17226/18612>
- Kim, K. H. (2006). Can we trust creativity tests? A review of the Torrance Tests of Creative Thinking (TTCT). *Creativity Research Journal*, 18(1), 3–14. https://doi.org/10.1207/s15326934crj1801_2
- Koehler, M. J., & Mishra, P. (2009). What is technological pedagogical content knowledge? *Contemporary Issues in Technology and Teacher Education*, 9(1), 60–70. <https://citejournal.org/volume-9/issue-1-09/general/what-is-technological-pedagogical-content-knowledge>
- Martin, L. (2015). The promise of the maker movement for education. *Journal of Pre-College Engineering Education Research*, 5(1), 30–39. <https://doi.org/10.7771/2157-9288.1099>
- Martinez, S. L., & Stager, G. (2013). *Invent to learn: Making, tinkering, and engineering in the classroom*. Constructing Modern Knowledge Press.
- National Academy of Engineering. (2004). *The engineer of 2020: Visions of engineering in the new century*. National Academies Press. <https://doi.org/10.17226/10999>
- Papert, S., & Harel, I. (1991). Situating constructionism. In I. Harel & S. Papert (Eds.), *Constructionism* (pp. 1–11). Ablex Publishing.
- Plucker, J. A., Beghetto, R. A., & Dow, G. T. (2004). Why isn't creativity more important to educational psychologists? Potentials, pitfalls, and future directions in creativity research. *Educational Psychologist*, 39(2), 83–96. https://doi.org/10.1207/s15326985ep3902_1
- President of the Republic of Uzbekistan. (2019). *Decree No. PF-5847 of 8 October 2019 "On approval of the Concept for the development of the higher education system of the Republic of Uzbekistan until 2030"*. National Database of Legislation of the Republic of Uzbekistan. <https://lex.uz/en/docs/6971334>
- R Core Team. (2023). *R: A language and environment for statistical computing* (Version 4.3.1) [Computer software]. R Foundation for Statistical Computing. <https://www.R-project.org/>
- Runco, M. A. (2014). *Creativity: Theories and themes: Research, development, and practice* (2nd ed.). Academic Press. <https://doi.org/10.1016/C2012-0-06920-7>
- Sawyer, R. K. (2012). *Explaining creativity: The science of human innovation* (2nd ed.). Oxford University Press.
- Scott, G., Leritz, L. E., & Mumford, M. D. (2004). The effectiveness of creativity training: A quantitative review. *Creativity Research Journal*, 16(4), 361–388. <https://doi.org/10.1080/10400410409534549>
- Sheridan, K. M., Halverson, E. R., Litts, B. K., Brahms, L., Jacobs-Priebe, L., & Owens, T. (2014). Learning in the making: A comparative case study of three makerspaces. *Harvard Educational Review*, 84(4), 505–531. <https://doi.org/10.17763/haer.84.4.brr34733723j648u>
- Stahl, G., Koschmann, T., & Suthers, D. (2006). Computer-supported collaborative learning: An historical perspective. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (pp. 409–426). Cambridge University Press. <https://doi.org/10.1017/CBO9780511816833.025>
- Tamim, R. M., Bernard, R. M., Borokhovski, E., Abrami, P. C., & Schmid, R. F. (2011). What forty years of research says about the impact of technology on learning: A second-order meta-analysis and validation study. *Review of Educational Research*, 81(1), 4–28. <https://doi.org/10.3102/0034654310393361>
- Torrance, E. P. (1966). *Torrance tests of creative thinking: Norms-technical manual*. Personnel Press.
- Voogt, J., & Roblin, N. P. (2012). A comparative analysis of international frameworks for 21st century competences: Implications for national curriculum policies. *Journal of Curriculum Studies*, 44(3), 299–321. <https://doi.org/10.1080/00220272.2012.668938>
- Wells, G. (2000). Dialogic inquiry in education: Building on the legacy of Vygotsky. In C. D. Lee & P. Smagorinsky (Eds.), *Vygotskian perspectives on literacy research: Constructing meaning through collaborative inquiry* (pp. 51–85). Cambridge University Press.
- World Economic Forum. (2023). *The future of jobs report 2023*. <https://www.weforum.org/publications/the-future-of-jobs-report-2023/>
- Zimmerman, B. J. (2002). Becoming a self-regulated learner: An overview. *Theory Into Practice*, 41(2), 64–70. https://doi.org/10.1207/s15430421tip4102_2