Building Critical System Thinking Capability in Engineering Students: A Case for Long- Term Tech Internships on Campus

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Abstract—**The rapidly evolving technology and business landscape necessitates the development of critical systems thinking skills among graduates to tackle complex, real-world challenges. This quantitative longitudinal study, spanning two years, explores the effectiveness of on-campus tech internships in enhancing systems thinking skills among 30 selected STEM students. Guided by expert mentors in system design, the internships addressed authentic problems with clear deliverables, supported by training, resources, access to facilities, and incentives for attaining pre-defined outcomes. Critical systems thinking was assessed using two parallel versions of the Engineering Systems Thinking Assessment (ESTA) to avoid familiarity bias, complemented by project journal evaluations on a continuous basis. Statistical analyses, including paired t-tests and ANOVA, demonstrated a significant enhancement in ESTA scores ($p < 0.001$), alongside notable outcomes: qualitative improvements in placement quality, patents filed, and improved standing in external hackathons. These results highlight the potential of long-term tech internships as a viable strategy to bolster graduate attributes, at least in small cohorts to begin with.**

Keywords—**Critical System Thinking; Engineering Education; Experiential Training; Engineering Systems Thinking Assessment (ESTA); Graduate Employability; Long term Internships.**

ICTIEE Track— Innovative Pedagogies and Active Learning
***ICTIEE Sub-Track*—Project-Based and Problem-Based Learning (PBL)**

I. INTRODUCTION

THE global technological landscape is undergoing rapid transformation, propelled by breakthroughs in artificial intelligence (AI), the Internet of Things (IoT), and Industry 5.0, which demand a workforce adept at navigating complex, inter-disciplinary and interconnected systems (UNESCO, 2023). These advancements have disrupted industries such as manufacturing, healthcare and transportation requiring engineers to design and manage systems that integrate diverse technologies seamlessly. The growth of critical systems thinking, which includes problem-solving, integration, and trade-off analysis, has become crucial to addressing real-world difficulties in engineering, where system design and development are fundamental. (Dugan and others, 2024). This skill set is essential to contemporary engineering education because it allows engineers to envision systems holistically, predict system behaviors, maximize performance, and innovate under pressure. But the rate of technological advancement frequently surpasses that of conventional curriculum, underscoring the pressing necessity of experiential learning strategies to close this gap.

Globally recognized accreditation bodies underscore this need. In India, under the Outcome Based education framework the accreditation bodies like National Board of Accreditation (NBA) lays stress on the solving of complex engineering problems and systems-based design as critical graduate attributes. Similarly, as per ABET, the premier accreditation agency in the United States, the key student outcomes include the ability to identify, design, and solve engineering problems, and to function on interdisciplinary teams, both of which are again rooted in systems thinking.

With more than 4 million students enrolled in the engineering programs in India, representing a significant portion of the global STEM talent pool, the need is more pressing. (AICTE, 2022). Although India positions itself as a potential leader in technological innovation, yet our higher education has often been criticized for failing to produce engineers with adequate skills. India's capacity to innovate beyond services and product engineering is also another concerning area. This challenge is further compounded by outdated pedagogical practices and inadequate practical training especially in resource-constrained institutions.

Innovative experiential models are required as the traditional pedagogical approaches based on theoretical learning often fail to bridge this gap. In this scenario, Long-term tech internships on campus appears to be a promising solution to enhance graduate attributes in this context. Such programs where students are made to work on real-world projects under expert mentorship help to foster critical thinking, practical skills, and

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industry alignment and addresses the employability demands of a technology-driven era (Romero et al, 2025).In addition, such initiatives also cultivate a problem-solving mindset that transcends classroom boundaries, preparing students for the interdisciplinary nature of contemporary engineering challenges. Despite their potential, the effectiveness of such initiatives in improving critical systems thinking among Indian engineering students remains underexplored, particularly given the unique socio-economic variation.

This longitudinal study examines a 2-year technology-internship program (June 2023 to June 2025) at an autonomous Indian engineering institution which offered mutli-disciplinary courses, involving 30 selected final and pre-final year engineering students mentored by experts in system design. Supported by resources like Coursera access, AWS, ChatGPT subscriptions, high-end workstations, and incentives such as IEEE/ACM memberships, the program was designed to develop system thinking capabilities among these selected interns. Students maintained project journals as part of continuous evaluation to track their learning and deliverables, yielding outcomes such as high-quality projects, improved placements, patents, and hackathon successes. This study contends that such internships can serve as a viable model to improve engineering education. This strategy might help to establish Indian higher education institutions as innovation hub spots by enhancing student skills through domain-expertise, deep engagement and mentoring and thereby contribute to the nation's technological leadership on the global stage.

The rest of the paper is structured as follows: Section II reviews the literature, Section III outlines the research design, Section IV presents quantitative results and implications, while section V concludes the paper.

II. REVIEW OF LITERATURE

Existing research in the domain, while not directly related to the current study, can be categorised into three broad areas.

A. Critical Systems Thinking and Cognitive Skill Development

Global studies increasingly emphasize the role of critical system thinking in preparing engineers for complex and technology-driven environments. The UNESCO Global Education Monitoring Report (2023) advocates experiential learning as essential for developing systems-level understanding in Artificial Intelligence, Internet of Things and Industry 5.0 domains, citing that conventional curricula lag behind evolving industry demands. Similarly, the World Economic Forum's Future of Jobs Report 2025 underscores the importance of analytical and creative thinking for emerging roles, with internships being increasingly used to address skill shortages in AI and semiconductor sectors (World Economic Forum, 2025).

Di Pietro (2022), through a systematic review in the Review of Education, observed moderate gains in students' problem-solving and critical thinking skills through international internships. However, the review cautioned against overgeneralization due to the predominance of self-reported data and limited evidence of long-term cognitive gains.

Chellappa et al. (2025), argue that generative AI demands a curricular revolution, emphasizing that internships, if integrated with personalized mentoring, can foster higher-order thinking. This aligns with NASA's 2025 internship programs, which promote deep learning through hands-on STEM research (National Aeronautics and Space Administration, 2025).

B. Mentorship and Institutional Support

Structured mentorship has emerged as a critical enabler of effective internship experiences. Schneider et al. (2024), through a series of focus groups in European contexts, found that mentorship quality and resource availability were directly linked to improved student outcomes. These findings resonate strongly in the Indian context.

A notable Indian contribution comes from Choudhary et al. (2024), who conducted a review of mentorship frameworks across institutions and demonstrated that the combination of institutional support and technology-driven mentoring tools significantly improved learning outcomes and student engagement. Their findings highlight that for mentorship to be effective, it must be intentional, well-resourced, and pedagogically aligned. Similar findings were reported by Gupta et al. (2025) where mentoring by successful Alumni when implemented in a structured manner showed significant positive impact on the student outcomes in the medium and long term.

C. Internship Delivery Models and Global–Local Alignment

The mode of internship delivery is also evolving to meet the needs of diverse learner populations. Marco et al. (2023) examined blended learning universities and found that integrating internships with online coursework deepens student engagement and facilitates skill transfer from theory to practice.

In India, several national initiatives reflect a shift toward scalable internship models. The 2025 Cisco Virtual Internship Program, aimed at 100,000 students, emphasizes remote learning and digital skills, while IIT Gandhinagar's 2025 B. Tech framework incorporates global exposure internships as a core curricular component (Indian Institute of Technology Gandhinagar, 2025)

Further, Chaudhuri and Bhandari (2024) in their Carnegie Endowment paper on iCET detail LAM Research's training of 60,000 engineers in semiconductor technologies, marking a clear shift toward industry-academia collaboration. However, as Mseleku (2024) notes in the South African context, the long-term impact of such internships remains underexplored in developing economies, particularly in terms of sustained cognitive outcomes.

III. RESEARCH METHODOLOGY

A. Research Design

This study adopts a quantitative, longitudinal case study design to assess the impact of long-term tech internships on building critical system thinking capability among engineering students at an Indian higher education institution. The approach relies on numerical data, using two parallel versions of the Engineering Systems Thinking Assessment (ESTA) to measure changes in graduate attributes over a 2-year period (June 2023 to June 2025), mitigating familiarity bias (Salkind, 2010).

The research questions are:

1.To what extent does participation in a 2-year tech internship program enhance the critical systems thinking capabilities of engineering students, as measured by the Engineering Systems Thinking Assessment (ESTA)?
2.How do long-term tech internships influence key graduate attributes, such as placement quality, project quality, and success in external competitions, among engineering students over a 2-year period?
3.What are the challenges in implementing such programs and enabling factors in their success?

B. Context and Participants

The study was conducted at a prominent Indian engineering institution from June 2023 to June 2025. Participants include 30 STEM students, selected based on their potential and observed performance, from programs such as Computer Science & Engineering and Electronics & Communication Engineering. The criteria such as academic performance, attendance, prerequisite courses, and faculty recommendations were taken into account. The internship program was mentored by five experts with proven credentials in system design and development, overseeing real-world projects with defined outcomes.

C. Workflow and Process

The tech internship program, branded as the "Directors Internship," was structured as a formal, professional initiative to enhance critical systems thinking among select engineering students. The mentoring team comprised five experts with significant system development experience in the IT industry, with over 60 years of combined experience in professional development roles, proven innovation credentials and domain expertise. Mentors were chosen through a rigorous internal review process based upon their demonstrated expertise, strong industry experience, prior innovation accomplishments, and their ability to guide students through complex, real-world engineering challenges. This team of experts conducted weekly reviews, presentations and set learning objectives and deliverables according to a structured schedule, ensuring consistent progress. Interns were granted time-off for academic activities to balance their internship and coursework commitments. The program was fully funded, covering equipment, consumables and institutional support for allied activities such as data collection, fostering a resource-rich environment. This and robust support, aimed to inspire a sense of prestige and drive the program's success.

D. Data Collection

1. *Pre-Intervention Baseline*
   To establish a baseline for critical systems thinking skills, Version A of the Engineering Systems Thinking Assessment (ESTA) was administered in June 2023. The ESTA, scored on a 0–160 scale, evaluates competencies such as integration, synthesis, trade-off analysis, and system behavior prediction (Frank, 2012). In addition to the ESTA, students completed a self-reported systems thinking confidence scale (5-point Likert scale: 1 = Not Confident, 5 = Highly Confident). Baseline data on key graduate attributes such as placement rates and project quality scores were collected to contextualize student readiness prior to the intervention.

2. *Intervention Implementation*
   During the two-year internship participants received targeted training and resources, including Coursera licenses, AWS credits, and ChatGPT subscriptions, as well as high-end workstations to ensure adequate computing power. Incentives such as IEEE and ACM student memberships were provided to encourage professional engagement. Working on authentic, industry-aligned problems, students maintained detailed project journals to log learning outcomes, weekly progress, and deliverables. Mentor-evaluators assessed each journal for the quality of systems-thinking application using a 0–100 rubric adapted from Richmond (1993), covering criteria such as feedback-loop identification, trade-off analysis, and holistic solution design.

3. *Post-Intervention Data*
   After June 2025, Version B of the ESTA was administered, and journal entries were scored to measure changes in critical systems thinking. Outcome metrics included project quality (mentor ratings), placement rates, patents filed and hackathon successes, collected from institutional records and external competitions.

E. Data Analysis

Quantitative Analysis

To evaluate the impact of the internship program, a paired t-test was conducted to compare pre-intervention (Version A) and post-intervention (Version B) ESTA scores, assessing improvements in critical systems thinking. Results were considered statistically significant at $p < 0.05$. A Pearson correlation analysis examined the relationship between the number of internship hours completed and the magnitude of ESTA score gains, providing insight into the dose–response effect of internship engagement.

To explore broader program outcomes, a one-way ANOVA was used to analyze differences in higher-order graduate attributes including patent filings, placement rates, and project quality between the pre- and post-intervention phases, with attribution to the internship experience. Additionally, mentor-assigned journal scores were correlated with ESTA outcomes to validate the alignment between theoretical assessment and practical application of systems thinking.

Validation The reliability of data was ensured through Cronbach's alpha (target > 0.7) for ESTA versions and journal scoring rubrics, with outlier analysis to guarantee the dependability of data (Richmond, 1993).

Version Equivalence In order to avoid familiarity bias while maintaining consistency in assessment, two versions i.e Version A and Version B of the Engineering Systems Thinking Assessment (ESTA) were created based on a balanced blueprint. Both versions adhered to the following principles:

- Equal domain weights (25% each)
- Matched cognitive complexity, aligned with Bloom's taxonomy
- Parallel scenario-based items to ensure contextual equivalence

Reliability and Item Analysis

Version A and Version B were developed as parallel forms with identical domain weights and matched cognitive complexity. The exact scenarios and questions differ, but both assess exactly the same systems-thinking competencies such that any improvement post the internship should not be attributable to item familiarity in Version A.

Both ESTA versions demonstrated high internal consistency, as measured by Cronbach's alpha:

Version A: α = 0.81

Version B: α = 0.84

As per the results of the Item-level analysis, the average discrimination index was consistent (0.43 for both versions) and the mean difficulty index was also similar across versions (Version A = 0.62; Version B = 0.65). These results therefore validate the use of both assessments to measure the longitudinal improvements in critical systems thinking during the internship program by confirming that they were psychometrically sound and statistically equivalent.

IV. RESULTS AND DISCUSSION

A. Quantitative Findings

This section presents the statistical results from the 2-year longitudinal study (June 2023 to June 2025) at an Indian engineering institution, assessing the impact of in-campus tech internships on critical system thinking among 30 STEM students using the Engineering Systems Thinking Assessment (ESTA) and project journals.

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B. Impact on Critical Systems Thinking

A paired t-test compared pre- (Version A) and post-intervention (Version B) ESTA scores to evaluate improvements in critical systems thinking. Table I displays the results.

TABLE I
PRE–POST COMPARISON OF ESTA AND CONFIDENCE SCORES WITH COHEN'S D

Variable	Pre-Intervention Mean (SD)	Post-Intervention Mean (SD)	t-value	Df	p-value	Cohen's d
ESTA Score (0-160)	85.3 (12.4)	112.7 (10.9)	9.87	29	< 0.001	2.09
Confidence Score (1-5)	2.9 (0.6)	4.2 (0.5)	8.45	29	< 0.001	1.54

Note: ESTA scores reflect integration, synthesis, trade-off analysis, and system behavior prediction. Confidence is self-reported on a 5-point Likert scale.

The results indicate a significant improvement in ESTA scores ($t(29) = 9.87$, $p < 0.001$) and confidence ($t(29) = 8.45$, $p < 0.001$), demonstrating enhanced critical system thinking. There was a large effect size in both ESTA gains ($d = 2.09$) and confidence improvements ($d = 1.54$), indicating substantial practical significance in addition to statistical significance.

C. Correlation Analysis

Correlation analysis assessed the relationship between internship hours and ESTA score gains, with journal quality as a complementary measure. Table II given below presents the correlation among the learning metrics.

TABLE II
CORRELATIONS AMONG LEARNING METRICS

Variable	ESTA Score Gain	Internship Hours	Journal Score (0-100)

ESTA Score Gain	1.00	0.76**	0.82**
Internship Hours	0.76**	1.00	0.70**
Journal Quality	0.82**	0.70**	1.00

**Note: *p < 0.01. Journal quality is a mentor-rated score based on systems thinking competency of students evidenced by journal entries and summaries.*

This relationship shows that the qualitative journal evaluations, indicating rigour and consistency, meaningfully complement and validate the quantitative ESTA results, confirming that measured cognitive gains were also manifest in actual project-based systems thinking practice.

A strong positive correlation exists between ESTA score gains and internship hours ($r = 0.76$, $p < 0.01$) and project journal quality ($r = 0.82$, $p < 0.01$), validating practical learning outcomes.

To further understand the contribution of internship-related factors to critical systems thinking development, a multiple linear regression analysis was conducted with ESTA score gain as the dependent variable. Internship hours and project journal quality were included as independent variables.

TABLE III
REGRESSION ANALYSIS

Predictor	β (Standardized Coefficient)	t-value	p-value
Internship Hours	0.53	4.07	<0.001 **
Journal Quality	0.41	3.14	0.004 **

The regression model was significant, $F(2, 27) = 26.41$, $p < 0.001$, with an $R^2 = 0.66$, indicating that 66% of the variance in ESTA score gain can be explained by the combination of internship hours and journal quality. Both predictors were statistically significant. Internship hours had a slightly stronger effect on ESTA improvement than Journal quality, suggesting that while time spent on the internship solving complex problems is the key factor, the quality of reflective learning through journalling played a crucial role in developing systems thinking.

D. Higher Order Outcomes

ANOVA compared pre- and post-intervention higher-order outcomes. Table IV given below summarizes the data

TABLE IV
ANOVA RESULTS FOR HIGHER-ORDER OUTCOMES AND EFFECT SIZES

Outcome	Pre-Intervention Mean (SD)	Post-Intervention Mean (SD)	F-value	df	p-value
Placement Rate (%)	65.0 (8.2)	84.5 (7.6)	28.93	1, 29	< 0.001
Patents Filed	0.0 (0.0)	0.1 (0.3)	3.45	1, 29	0.073
Hackathon Wins	1.2 (0.4)	2.8 (0.6)	45.12	1, 29	< 0.001
Project Quality (0-100)	72.4 (9.1)	88.6 (7.3)	32.67	1, 29	< 0.001

Note: Placement quality is measured as the median salary of the cohort over students who were not a part of the internship program; patents are average per student; hackathon wins are absolute numbers and project quality is determined through rubrics.

Significant improvements were observed in placement median salaries ($F(1, 29) = 28.93$, $p < 0.001$), hackathon wins ($F(1, 29) = 45.12$, $p < 0.001$), and project quality ($F(1, 29) = 32.67$, $p < 0.001$), with a marginal increase in patents ($p = 0.073$). The effect sizes for the placement median salary, patents filed, hackathon wins, and project quality were 0.50, 0.11, 0.61 and 0.53. All major outcomes showed large effect sizes ($\eta^2 = 0.50$–0.61) except patents, where gains were marginal ($\eta^2 = 0.11$), indicating the complexity in the patent filing process and the opportunity for innovation in select projects. The modest gain in patent filings suggests that innovation outputs are best produced with longer time frames, deeper domain expertise, and sustained mentoring beyond the internship period. Future iterations may integrate innovation workshops and industry mentorship structured into project-based learning and industry internships to strengthen patentable outcomes. This supports the strong influence of rigorous internships based on deep engagement on employability and performance.

E. Discussion

The statistical results affirm that the tech internship program significantly enhanced critical systems thinking—evidenced by a 32% rise in ESTA scores (from 85.3 to 112.7) and increased student confidence. This aligns with Kolb's Experiential Learning Theory, which implies that learning is maximized through a continuous cycle of concrete experience, reflective observation, abstract conceptualization, and active experimentation (Kolb, 2010). The strong correlations between internship hours, ESTA gains, and journal quality ($r = 0.76$–0.82) reflect how sustained engagement and guided reflection fuel deeper cognitive development, a conclusion also supported by Barr et al. (2025) in their longitudinal study of work-based learning. Higher-order outcomes, including a 30% increase in median salaries for the internship cohort over the non-control group, placement rates and two hackathon wins at the national level with significant cash prizes, compared to zero for the non-control group, affirm that structured internships foster employability and innovation (Araújo et al., 2025; NACE, 2024). The modest gain in patent filings is consistent with Edison et al. (2018), who note that innovation outputs such as patents require extended mentoring, institutional resources, and iterative ideation cycles.

There were certain challenges that emerged during implementation which included scheduling conflicts with academic commitments, varied levels of student preparedness, and coordination gaps between mentors and interns. These were resolved through flexible scheduling, additional preparatory sessions, weekly structured reviews, and continuous communication with mentors so as to ensure alignment throughout the internship

F. Implications

The study's findings underscore the viability of long-term tech internships in building critical systems thinking, offering a model for engineering education. However, a caveat to formulating and implementing such programs is the quality of mentors available and the professional management of the internship structure. High-caliber mentors with expertise in system design ensure rigorous guidance, as supported by research on mentorship quality in STEM education (Felder & Brent, 2005). Effective management, including clear deliverables and resource allocation, is critical for success, aligning with studies on structured internship programs (Sweitzer & King, 2004). Moreover, the environment created should inspire a sense of prestige among students, fostered by strong recognition and rewards programs, such as IEEE/ACM memberships and access to Coursera subscription, which enhance motivation and professional identity (Tinto, 1993). Institutions, especially in India, must invest in mentor training and robust administrative support to replicate this model, ensuring scalability and relevance in a technology-driven landscape as of June 2025.

G. Limitations

First, this model works well in smaller cohorts and is not linearly scalable. It is recommended as an enrichment program for institutions looking to enhance the attainment levels of their best students in terms of defined student success outcomes through deep engagement. There was no formal control group, but the outcome variables of placement quality and hackathon performance from the non-intern batches provided benchmarks. Differences were addressed through pre–post comparisons within the intern group and ANOVA analyses against non-intern cohorts.Once a culture of excellence is established it can organically filter through the rest of the institution. Such models can lead to attracting better quality students, which in turn will help strengthen the institutional reputation in the long term. The study's focus on 30 students limits its applicability to larger groups without significant resource adjustments, and the intensive mentorship and infrastructure demands may pose challenges for broader implementation. This study may also be affected by selection bias, as students were chosen for the internship program based on academic and attendance criteria, which may limit the generalizability of the findings.

CONCLUSION

This longitudinal study conducted over two years (June 2023 to June 2025) at an Indian engineering institution demonstrates the transformative potential of long-term tech internships in cultivating critical systems thinking among 30 STEM students. The significant improvement in Engineering Systems Thinking Assessment (ESTA) scores, a 30% increase in placement quality, doubled hackathon successes, and significantly enhanced project quality underscore the program's efficacy in enhancing graduate attributes. However, the success of such programs hinges on the quality of mentors, necessitating rigorous selection and training to ensure expertise in system design, including clear deliverables and resource coordination For Indian higher education, scaling this model shall require institutional investment in mentor development, administrative support, and deep commitment to student success. The potential long-term outcomes from such programs make such an intervention worthwhile. Further research could develop and test scalable variations of this framework, assess longer-term career outcomes, and investigate generalizability in diverse settings for increased reach.

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