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An AI-Driven Adaptive Gamification Framework for Systematic Improvement of Critical Thinking in Engineering Education

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***Abstract*— This research project describes an AI-based adaptive gamification platform that was developed, implemented, and validated to develop critical thinking skills including problem-solving and analytical reasoning, among undergraduate engineering students. Across three fields of theoretical foundation, cognitive load theory, self-determination theory, and constructivist learning tenets, the AI-based adaptive gamification platform has provided personalized challenges, feedback and social learning engagement. Furthermore, the application of the adaptive gamification platform was applied within the context of educational engagement on two university undergraduate engineering courses. Following a mixed-methods approach, a 12-week intervention with 120 students was conducted, integrating the adaptive gamification platform into the design of the undergraduate engineering courses. The study included a variety of quantitative measures pre and post intervention, longitudinal and cross-sectional, and assessment of engagement through measures of earned points, milestones, and sessions completed. The statistical analyses were significant across all components of critical thinking development (i.e., Problem Identification, Solutions Development, Solutions Evaluation, Decisions, Plans and Evidence Evaluation, and Final Decision) and averaged 22.9% improvement in performance on critical thinking activities (Effect size Cohen's d = 2.436). The project demonstrated the capacity for AI gamification to have a transformational impact on engineering education enabling the development of higher order cognitive skills and demonstrated clear implementation pathways for scaled transformative impact within individual university courses and developing a longer-lasting footprint within an institution.**

***Keywords*— AI-driven gamification; Adaptive learning; Analytical reasoning; Critical thinking; Educational technology; Engineering education; Problem solving; Student engagement.**

I. INTRODUCTION

As engineering practices continue to evolve, educators continue to encounter a myriad of obstacles in indoctrinating graduates with higher order problem solving and analytical reasoning skills. Traditional instructional methods do not often achieve success, warranting a shift toward the use of artificial intelligence (AI) and gamification-based interventions [1].

Furthermore, accreditation standards such as ABET have set expectations of employers' skill requirements of engineers who are critical thinkers, identifying the discrepancy between employers' expectations of degree graduates' skills sets [2]. The goal of this research is to address this gap in regard to providing personalized game-based AI learning to promote long-term development of foundational competencies for engineering purpose statements. There is an increasing uptake of artificial intelligence and machine learning in engineering education, specifically due to the opportunity for data rich learning experiences [3]. The ability to personalize educational content and the opportunity for the AI to adapt, is a direct engagement with the student experience and student learning outcomes [4]. The introduction of educational material related to AI, specifically generative AI, in computer science and engineering courses is an emerging research field to understand the effectiveness, importance, support and impact AI is having on student learning and skill development [5] [6]. The result is educational stakeholders are re-imagining approaches to education in order to create student experiences laden with AI and consider the educational ethical implications of AI [7] [8].

That said, the concerns of ethics associated with the potential over-proliferation of artificial intelligence and its tools are still present, and therefore a calibrating approach that respects the human intentions of the intended learning is recommended [9]. In this paper, we intend to examine whether AI based adaptive learning, and Gamification can sustainably work together with the goal of develop the competences that are characteristics of the continuum that is seen in engineering education where we would create technically competent and ethically and flexibly practicing graduates [10] [11]. Recognizing that part of that continuum also explains that students will need to acquire AI Literacy, critical thinking, and ethical Artificial Intelligence skills for working successfully in appropriate engineering situations [12]. Also, artificial intelligence has the ability to develop complex assessments of cognitive performance along with personalized content in ways that would not be possible with traditional applications [13]. Also, this systematic approach utilizes AI's adaptivity to develop content and offer feedback that meets the needs of all learners, maintains the learning experiences of learners, creates efficiencies in learning, and mitigates negative outcomes (e.g. algorithmic bias, data privacy) that hand generated alternatives would not [14] [15]. Accordingly, we conclude that the research is intended to provide a framework to consider an appropriate and ethical use of artificial intelligence and gamification technologies in engineering education.

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II. LITERATURE REVIEW

The current literature review will conduct a review of the literature of AI in education. The focus will be on adaptive educational systems and gamification in order to provide a context for adaptation for engineering programs [16] [17]. It will highlight AI personalized learning, but the purpose here is to show its delivery with the educational ethical implications in mind with regards to algorithmic bias, and data privacy issues [18] [19]. AI driven personalized learning, leans on adaptive content deliverance, real time feedback, and intelligent tutoring systems to form personalized educational experiences that are tailored to each students needs and their interests - thus optimizing performance levels and reducing disrupted educational experiences [20] [20]. AI driven personalized learning provides enhanced educational delivery opportunities which can promote increased student engagement combined with improving academic performance through personalisation of their learning experiences [21]. Adaptive learning, coupled with intelligent tutoring systems, encourages personalized learning environments and mitigates the challenges of teacher shortages, improving the educational experience [22]. Adaptive learning systems may be adjusted to a student's individual pace or learning style through their ability to intervene at key points in the learning process, adapting their content into tailored and adjusted solutions to enable the maximum degree of understanding and retention of the learning experience [16] [23] - therefore developing past a pre-defined assessment design constructed on a traditional, one-size-fits-all instruction [22]. Research has shown that personalized instructional methods utilizing AI will frame learner engagement and outcomes in a more effective manner [24]. AI-based solutions can personalize feedback to meet their individual learning needs while enhancing educational outcomes, despite the ethical and data privacy issues that must be addressed [25]. However, realizing these genuinely individualized learning experiences necessitates addressing impediments such as ethical implications, potential bias, and an overreliance on AI [26] [27]. AI technology is being used to tailor educational material and experiences to individual learner needs, styles and preferences, thereby improving engagement and student outcomes [28]. Tailoring focuses on the diversity of the student population; students have individual strengths and weaknesses, which need to be taken into consideration [29, 30]. Further, through analyzing performance data AI can recognize knowledge gaps and provide resources to students [25]. AI is analyzing educational data, such as student behaviors and learning styles, to provide personalized recommendations and modify teaching modules, all situated within an adaptive learning environment [31]. Adaptive learning environments are particularly beneficial in engineering education, where learners are frequently faced with new and complex concepts and need to be able to proceed at their own pace and from multiple modalities of teaching [32]. An Artificial Intelligence powered platform, results with machine learning, and data analysis as it occurs in real-time through interaction with students, where they too can be considered to be achieving what they call " a personalized experience" that is provided to students at the right level of difficulty, and retrospective personalized feedback [33]. Although these factors have been treated, there are numerous aspects of support for, and bias related to, learning motivation are largely not addressed [34]. With this in mind, it is important to consider the complex, dual nature of A.I. in personal learning [15]. The remainder of this literature review paper will consider gamification strategies that will enhance student engagement, motivation, and the overall learning experience with game design elements for use in a learning environment. This method involves student-centered games with the individualized approach of AI and the positive features of gamification to increase learner development and engagement for solving problems without restrictions on applying their learning in a more unintended productive way [35] [36]. The combination of these features can promote the learning of higher order thinking, including reflective thinking, critical thinking, problem-solving, and analytic reasoning skills, which are essential skills needed in such engineering disciplines today [34] [37].

III. PROPOSED SYSTEM

The research design encompasses the conception, design, and execution of a new AI-enabled adaptive gamification framework with the goal of developing students' critical thinking skills in engineering education with an emphasis on problem-solving and analytical reasoning. This was part of the proposed work and describes the theory, the theoretical and practical gamification framework we created for engineering students, and the strategies we then utilized to enact the framework in a higher educational context.

The proposed work is intended to face the historical issues associated with the insufficient development of critical thinking competencies required by students for modern engineering practice. Much of the existing curriculum, pedagogical, and assessment strategies do not sufficiently develop complex cognitive skills such as reasoning under uncertainty, reasoning with system-level decompositions of the problem with respect to identifying the intended design functional principles, and decision-making with respect to potential design solutions created with multidisciplinary interactions and constraints. The use of AI and gamification represents a new approach to the problem by creating personalized experiences that dynamically respond to individual student needs, while remaining actively engaged through aspects of play and game mechanics. The primary goal is to develop and validate an AI-powered adaptive gamification framework that actualizes the development of critical thinking competence using an organized, six-phase process. This framework exemplifies how engineering experts adopt systematic approaches to engineering problems, from awareness and framing of problems to continuously monitoring their solutions. The work is framed on established educational theories (i.e., cognitive load, self-determination, and constructivist learning) that informed the design and educational fidelity of the framework.

Complete Gamification Framework for Critical Thinking

The proposed gamification framework is structured in six phases of engineering problem solving:

1. Problem Recognition: Recognition of the problem and various contextual factors associated with the problem including the stakeholder context and the factors in the physical environment that are driving the problem.
2. Problem Decomposition: Decomposing a complex problem into sub problems or components that can be analyzed individually.
3. Solution Generation: Generating several potential solutions based on creativity, feasibility, and sound engineering practice.
4. Solution Evaluation: Evaluating solutions created against recognized criteria and identifying the risks and justifying the decision made.
5. Implementation Planning: Planning for using the solutions in the real-world context including assets, time allocation, and planning for the potential implementation risks.
6. Solution Monitoring: Monitoring the solution use in the real-world context continuously so that they can adaptively refine their solutions and consider their problem solving.

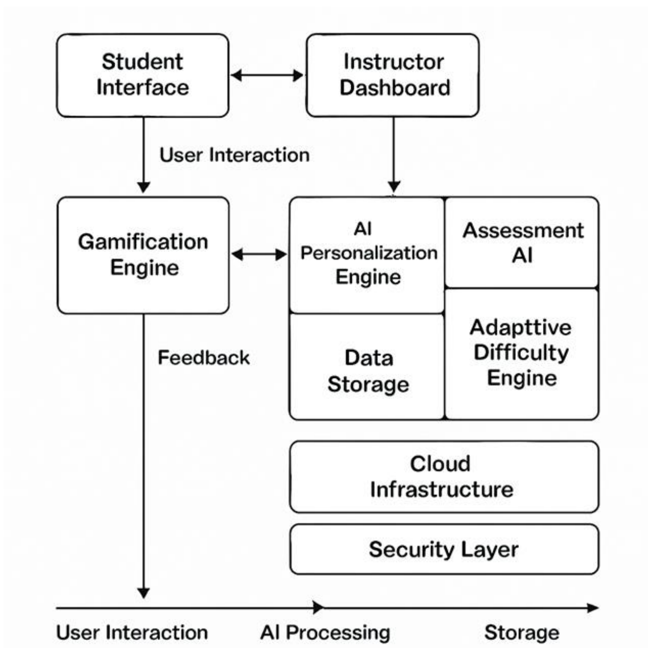

Fig. 1. System architecture of the AI-driven adaptive gamification framework

The proposed system architecture or framework as in fig 1 illustrates user interaction (student interface, instructor dashboard), the gamification engine, integrated AI modules (personalization, assessment, adaptive difficulty), and supporting infrastructure (data storage, cloud, security).

Key Gamification Elements

The framework used incorporates several gamification elements to reward and motivate students as they progress through their work.

• Points System: The points system works on multiple dimensions: first by providing base points based on the complexity of the problem; and second, by providing additional points contingent upon strength of analysis, collaboration, persistence and solution quality. For every phase and problem there is a fixed number of points; therefore, each phase of the progression has a fractional part of the total number of points, encouraging students to be well rounded within the competencies.

• Badges: Badges are visual representations of various successes for the coverage of attributes such as analytical thinking, innovation and creativity in problem-solving, collaborative task fulfilment, and resilience in a growth mind-set as students make their way through the frameworks.

• Leaderboards: Leaderboards include various rankings based on strengths and preferences (overall critical thinking scores, cost-benefits between speed and accuracy, team strengths, or adaptive thinking capacities).

• Adaptive Challenge Breakdown: The framework incorporates a number of ways to break down challenges that students are working through (e.g., removing scaffolding, progressively introducing complexity, restricting timeframes, etc.) so that students are working on problem and challenge tasks that are situated at the optimum load and engagement levels.

Engagement and Motivation Mechanics

The mechanics of engagement and motivation are governed by an engagement narrative about the anchor problem to convey it through authentic engineering problems (e.g.; crisis, innovation) to add relevance and empathy. Online social collaborative tools enable peer learning through practices, such as think-pair-share, expert coaching and mentoring, and developing and sharing problem galleries.

The structure supports autonomy by allowing students to choose problems that align with their interests and methods of learning. Feedback is immediate and specific to the individual learner using AI based analytics and uses engagement and motivation measures as indicators for success. More specific and immediate feedback can help students update their methods and tools based on where they stand in each moment.

Assessment Integration

Assessment is integral to the design following a six-phase process involving assessment rubrics, made explicit by experts and supported by AI-supported analytics. Students are assessed on the accuracy of their identification of problems, clarity of problem decomposition, the creativity and feasibility of their solutions, the rigor of their evaluation, the quality of their implementation plan, and the effectiveness of the monitoring. AI tools such as natural language processing are used to assess students' written responses to measure degrees of conceptual understanding and understand the reasoning chains they used during their assignments. Behavioral data also captures the students' persistence and adaptive strategy use.

Adaptive Personalization

Using AI algorithms, which included k-nearest neighbors (k-NN), reinforcement learning, and Bayesian networks, the framework would personalize the learning experience for each user based on their cognitive profiles, learning preferences, and motivation. This included dynamically changing the level of challenge users encounter during the learning experience, changing the level of engagement features users would encounter, and personalizing modalities of feedback. The learning experience was designed for accessing diverse cultural backgrounds and accommodating diverse accessibility needs to ensure equitable learning opportunities.

Implementation Approach

The implementation approach to this framework can be outlined in three phases: design and development, pilot implementation, and iterative refinement from empirical data.

Design and Development

The first phase involved creating a modular software platform with all the designed mechanisms of gamification, AI personalization, and assessments that were described above. Educational goals were created, along with problem libraries, in collaboration with engineering educators and industry experts for authenticity and accreditation purposes (e.g., aligned with ABET).

AI models for learner modeling and customized difficulty adjustment were trained based on learner history and verified using simulation studies. Narrative content and collaboration affordances were developed and tested in a cycle of usability testing and effectiveness for engagement.

Pilot Deployment

Two engineering courses, Design Thinking and Industrial Internet of Things (IIoT) were coordinated based on the framework at an undergraduate level. They operated over a twelve-week semester working with 120 students through different engineering problems in a six-phase process.

Data collection instrumented learning analytics that reported performance, engagement, and behaviors in relation to the three constructs as well as pre- and post-intervention tests that reported critical thinking gains.

Data Analysis and Adaptation

Our statistical analysis measured efficacy of the framework over the twelve-week semester that measured improvement in scores across phases, distributions of performance across phases, and the correlation of gamification elements (points, badges) with learning outcomes. Engagement and motivation were surveyed based on the constructs in self-determination theory.

Feedback from students and faculty have been used to iteratively update, improve, and expand the challenge scaling algorithms and the timing of feedback, and features that allowed for social collaboration. The iterative refinement process that we engaged in included A/B testing of the gamification and continuous updates to the AI algorithm for the personalization model.

This iterative refinement process is a representation of a continuum between theoretical and semi-practical work and has culminated in an AI-adaptive gamification model that can inform a relevant approach to developing better critical thinking skills in engineering education. This model borrows several capabilities from many gamification models, uses AI to build a personalization model, and considers normalizing for activities that provide practical, real-world action processes. This multi-layered framework has laid the groundwork for scalability and sustainability in education.

IV. RESULTS AND DISCUSSIONS

The implementation and evaluation of the AI-driven adaptive gamification framework demonstrated excellent results in improving critical thinking skills for engineering students. Conducted over 12 weeks, a total of 120 students across two undergraduate courses, Design Thinking and Industrial Internet of Things (IIoT). The framework demonstrated statistically significant improvement across all 6 phases of the critical thinking model including problem recognition, problem decomposition, solution generation, solution evaluation, planning for implementation, and monitoring solution. Figures 2 and 3 are the screenshots of phase 1 and phase 6 respectively.

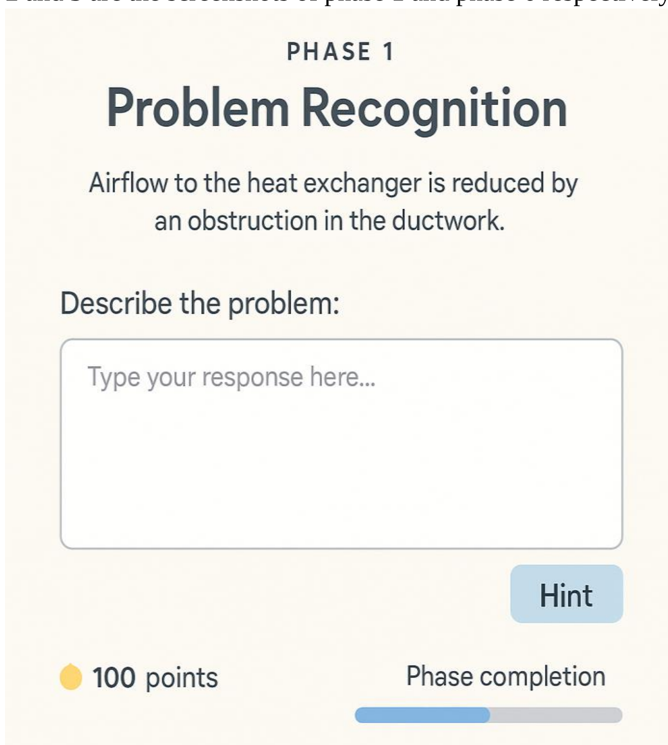

Fig. 2. Problem Recognition screen (Phase 1)

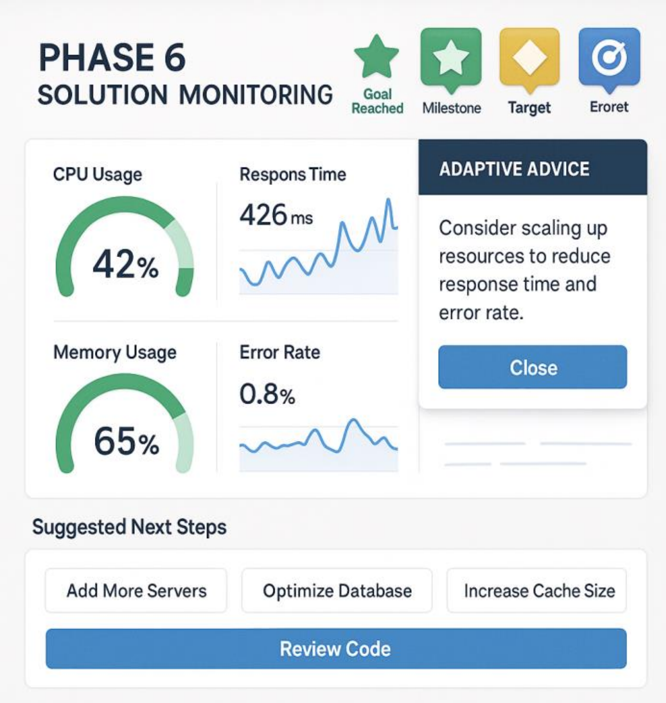

Fig. 3. Solution Monitoring screen (Phase 6)

Six-Phase Improvement: Each of the phases demonstrated significant improvements as in fig 4, with solution evaluation showing the most improvement at 27.5%, followed by implementation planning (26.2%) and solution monitoring (24.7%). In total, the cohort exhibited a 22.9% gain in critical thinking scores (mean difference of 14.15 points), which resulted in a very large effect size (Cohen's d = 2.436) having very strong statistical significance ($p < 0.001$).

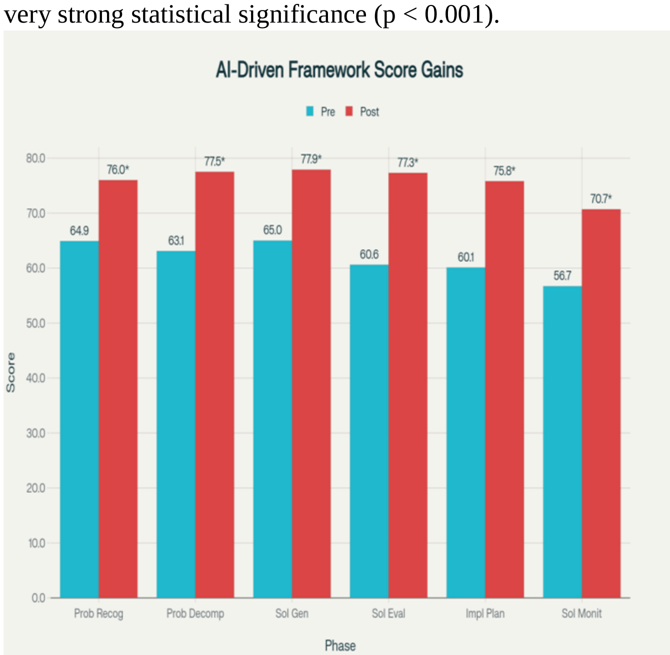

Fig. 4. Six-Phase Critical Thinking Framework: Pre vs Post Assessment Results (120 Students)

Shift in Distribution of Performance: It was just as impressive to see that the students labelled below average decreased from 44.2% of all students prior to assessment to only 4.2% of all students after assessment, and the students labelled excellent increased from 6.7% of all students to 34.2% of all students. There was an amazing increase in student performance as represented in fig 5.

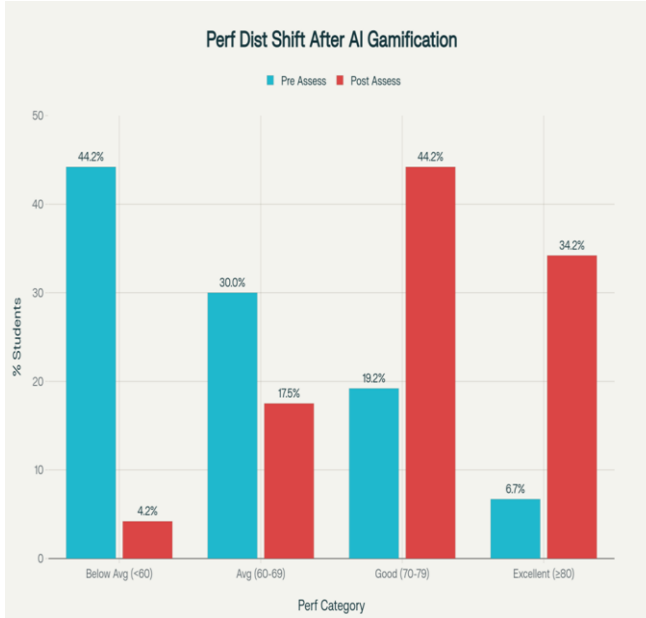

Fig. 5. Student Performance Distribution: Before vs After AI Gamification Framework.

Course-specific results (fig 5): All findings come from the Design Thinking and Industrial IoT courses. In the Design Thinking course, there was a 20.2% increase, with 73.3% of students (based on proposed improvement score of 10+ points) showing some improvement in their score in the post survey. On the Industrial IoT course, there was a higher level of improvement of 25.7% and a higher percentage of students successful (86.7%), both indicating a range of effectiveness for all aspects of the curriculum offered.

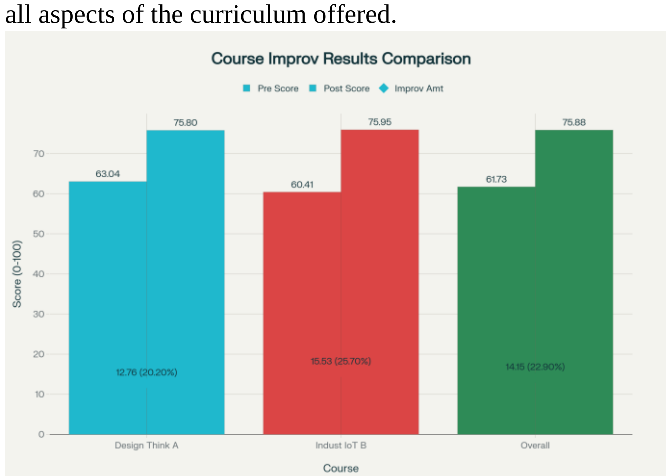

Fig. 6. Course-Specific Critical Thinking Improvement Results

Engagement and motivation correlates: For the engagement analysis, students had significant, positive relations to learning gaine, total points earned (r = 0.452), number of sessions (r = 0.404) and perceived autonomy (r = 0.387). On average students earned 4,089 points, earned approximately 8.1 badges, and engaged with the learning platform for approximately 28.6 minutes per session collectively indicating students continued to have motivation and engaged in the platform. This is visualized in fig 7.

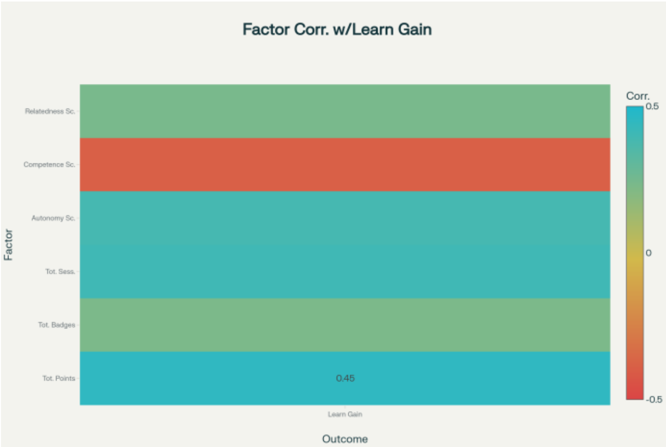

Fig. 7. Engagement and Motivation Factors: Correlation with Critical Thinking Improvement

- Adaptive difficulty, personalized feedback provided through artificial intelligence, and different multidimensional gamified aspects of the framework, helped ensure meaningful challenge and the engagement of students.
- The badges and leaderboard types for individual and team success, with the four-set of rubrics, made the framework more holistic and encouraged team and individual achievement.
- The assessment dimension intertwined the integrated AI analytics with evidence-based or recognized/global rubrics to provide evidence-based information regarding the cognitive development and problem-solving skills of students. Real-world evidence demonstrated the success of the AI supported adaptive gamification framework which is a novel and disruptive approach to teaching that enhances the acquisition of critical thinking skills is engineering education. The significant improvement of 80% of participants and most demonstrated some level of higher-order cognitive skills from all six phases of development, suggest that the framework and model offers a scalable, evidence-based means to innovate and drive changes in engineering education practices. With these positive impacts, demonstrated evidence was provided to scale up and investigate longitudinally effects and impacts of other disciplines.

Conclusion and Future scopes

The AI based customizable gamification framework resulted in significant improvement in critical thinking, problem-solving drivers, and reasonable analytical reasoning for all parts of engineering education studied. The results showed a mean increase of 22.9% pre to post-assessment performance with large effect sizes and significance($p < 0.001$). It should be noted that the Intervention Planning and Solution Evaluation phases showed the largest gains, and the number of students categorically defined as performing in the "excellent" category increased by over 400%.

It is clear that the gamification framework was able to provide both greater learning outcomes and sustainable motivation. Engagement was measured with numerous metrics (e.g., session frequency, autonomy) which were all shown to highly correlate with the assessment results of improvement. My expectation of the system to work for all learners was met, and all learners, regardless of their learning style were engaged with learning without cognitive overload. Several emerging learning behaviors were observed through collaborative learning features and using traditional gamification metrics (e.g. points, badges, leader boards).

Limitations included brevity and the need for further exploration into individual learner variance and ethical concerns. More research is necessary to explore the applicability of the framework across contexts and over time. Future research will examine the value of longitudinal studies in measuring skill retention and transfer patterns to real-world applications, improve the personalization algorithms to include cultural differences and individual nuances, and explore scalable implementation possibilities. A more rigorous and comprehensive faculty development program and ongoing ethical oversight will be important in the age of AI-assisted gamification of engineering education. This study confirms that the framework is ready for broad implementation as well as a notable opportunity to change how critical thinking is cultivated in future engineers.

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