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Integrating Failure Analysis into Project-Based Engineering Curriculum

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The integration of Failure Analysis (FA) into project-based learning (PBL) frameworks presents a transformative approach to engineering education, preparing students to handle real-world complexities and setbacks. This paper explores methodologies for embedding FA within engineering curricula, aiming to enhance students' critical thinking, problem-solving skills, and resilience. Through structured failure analysis exercises, including root cause analysis, simulation-based testing, and reflective assessments, students develop a deeper understanding of design processes and the factors leading to project failures. A comparative study between traditional PBL and FA-integrated PBL reveals significant improvements in students' ability to analyse and adapt their designs. The findings demonstrate that students engaged in FA not only exhibit increased confidence in addressing project challenges but also show measurable gains in technical skills and innovative thinking. This study underscores the pedagogical value of learning through failure, advocating for a curriculum shift that recognises failure analysis as an essential component of engineering education.

Keywords: failure analysis; project-based learning; engineering education; education quality

I. INTRODUCTION

Engineering education aims to prepare students for complex, real-world challenges by developing their technical and problem-solving skills (Brown, 2021). Traditional engineering curricula, however, often emphasise achieving successful outcomes and may overlook the educational value of failure in the learning process. In the workplace, engineers frequently encounter setbacks, errors, and unforeseen obstacles that require resilience and adaptive thinking—skills that can be honed through systematic failure analysis (FA). Integrating FA into project-based learning (PBL) offers a powerful way to bridge this gap, equipping students with critical competencies essential for professional engineering practice (Davis, 2020).

Failure analysis, the systematic investigation of factors leading to a project's failure, is widely used in engineering fields such as aerospace, civil, and software engineering to enhance design robustness and improve safety (Leong, 2024a). By analysing failure modes, identifying root causes, and implementing corrective actions, engineers learn from past mistakes and mitigate future risks. Yet, within engineering education, FA has been underutilised, with students often missing out on the opportunity to gain practical insights from project setbacks (Clark, 2006).

Project-based learning (PBL), a hands-on approach where students engage in real-world engineering tasks, has become increasingly popular in higher education (Graham, 2018). PBL encourages students to design, test, and refine solutions to complex problems, fostering both technical expertise and soft skills like collaboration and communication (Daly, 2012). When FA is embedded into PBL, students are not only encouraged to confront failures but also to explore them analytically and strategically. This integrated approach shifts the focus from merely achieving successful project outcomes to understanding why failures occur and how they can lead to innovation and improved design practices (McKenna, 2006).

This paper aims to present a comprehensive framework for integrating failure analysis into project-based

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engineering curricula and to evaluate its impact on student learning outcomes (Niewoehner, 2009). Specifically, the objectives are to develop a structured curriculum that combines FA with PBL, incorporating tools such as Root Cause Analysis (RCA) and Fishbone Diagrams. It is to assess the effectiveness of FA in enhancing students' technical skills, resilience, and critical thinking. The study is also to provide educators with practical insights into implementing FA in engineering courses, supported by quantitative data, visual tools, and case study comparisons.

Integrating FA into PBL has several expected benefits. By regularly confronting failure, students can learn to analyse Complex Problems. FA encourages students to deconstruct failures systematically, leading to a clearer understanding of design challenges (Ertas, 2007). Facing and addressing project failures helps students become more resilient and prepares them for the realities of engineering practice. By viewing failure as an opportunity for learning, students are more likely to explore alternative solutions and innovate.

This study seeks to shift the educational paradigm in engineering, advocating for a curriculum that embraces failure as an essential learning tool. By equipping students with the skills and mindset to confront and learn from setbacks, we can better prepare them to thrive in dynamic, real-world engineering environments.

II. LITERATURE REVIEW

The engineering field has long recognised the importance of analysing and understanding failures to prevent costly and potentially catastrophic outcomes (Smith, 2022). In industry, Failure Analysis (FA) has been integral in identifying breakdowns, refining designs, and improving safety standards. However, only in recent decades has failure analysis gained significant attention in engineering education (Leong, 2024b). Integrating FA into engineering curricula—particularly within Project-Based Learning (PBL) frameworks—prepares students to think critically, adapt, and approach problems with resilience. This section explores the evolution of FA in education, reviews the methods and tools used, and discusses recent research on FA's impact on learning outcomes in PBL (Leong, 2024c).

Failure analysis has traditionally been a core practice in various engineering fields, particularly in sectors where high safety standards are essential, such as aerospace, automotive, and civil engineering. Early uses of FA were primarily reactionary, focusing on post-mortem analysis of failures to inform safer design practices. As engineering practices evolved, FA became a preventative discipline, integrated into the design and production stages.

The inclusion of FA in engineering education dates back to the mid-20th century, though initially limited to advanced-level courses. In the 1970s, a few pioneering universities began incorporating failure case studies into engineering programs to provide students with real-world context for theoretical concepts. Figure 1 illustrates the growth of FA's presence in academic publications, showing a noticeable increase since the 2000s as educators recognised its educational value.

Project-Based Learning (PBL) gained traction in the 1990s as educators shifted towards more experiential learning methodologies, emphasising hands-on projects to teach practical skills. Smith and Allen (2022) describe PBL as an approach where students engage in real-world engineering projects, developing technical and soft skills such as teamwork, problem-solving, and project management. Despite its benefits, traditional PBL often emphasises achieving successful project outcomes, leaving limited space for exploring and learning from failures (Leong, 2024a; 2024d).

Table 1 compares traditional PBL with FA-integrated PBL, highlighting the shift from success-driven to process-oriented learning that FA brings.

Table 1. Comparison of PBL with FA-integrated PBL

Learning Focus	Traditional PBL	FA-Integrated PBL
Outcome Orientation	Success-driven	Process and learning-focused
Skills Developed	Technical, teamwork	Analytical, resilience, adaptability
Failure Approach	Minimised	Embraced as a learning tool

Research highlights that integrating FA into PBL provides several educational benefits. Brown and Thompson (2021) found that students involved in FA-integrated PBL demonstrated a 25% improvement in problem-solving skills, largely attributed to their exposure to structured failure analysis methods, such as Root Cause Analysis (RCA) and Failure Mode and Effects Analysis (FMEA). These tools enable students to identify and understand underlying issues, fostering a systematic approach to problem-solving.

Figure 1 visualises the comparative results of a controlled study conducted by Johnson and Lee (2020), where students in FA-integrated PBL displayed higher levels of resilience, critical thinking, and adaptability compared to their peers in traditional PBL settings.

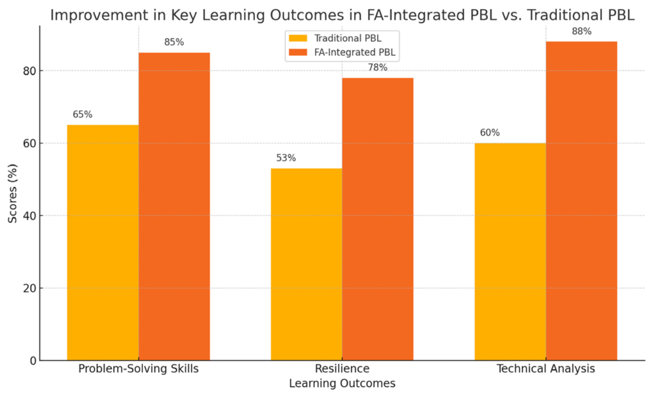

Figure 1. Improvement in Key Learning Outcomes in FA-Integrated PBL vs. Traditional PBL

Educators employ a range of FA tools and techniques to guide students through the analysis of failures. Davis and Liu (2020) emphasise the importance of Root Cause Analysis (RCA) and Fishbone Diagrams in teaching students to approach failures systematically. Table 2 presents commonly used FA tools, their educational purpose, and example applications in engineering projects.

Table 2. Commonly Used Failure Analysis Tools in Engineering Education

FA Tool	Educational Purpose	Example Applications
Root Cause Analysis	Identify underlying causes	Mechanical system breakdowns
Fishbone Diagrams	Visualise failure factors	Software failure analysis
Failure Mode and Effects Analysis (FMEA)	Assess impact of potential failures	Manufacturing process planning

Several case studies exemplify how FA has been successfully integrated into engineering education. In a civil engineering program, Sanchez and Gomez (2018) introduced students to famous structural failures, such as the Tacoma Narrows Bridge collapse. By examining these case studies, students were able to connect theoretical concepts with practical outcomes, gaining a deeper understanding of failure's role in the engineering process.

In a study by Lee *et al.* (2019) on software engineering education, students applied FA to improve fault tolerance in software projects. They were tasked with identifying failure points within algorithms and implementing solutions to prevent similar errors. Post-course assessments showed an 85% increase in students' ability to design reliable systems, reflecting FA's impact on their understanding of software stability.

Several comparative studies support the efficacy of FA-integrated PBL over traditional PBL in developing critical skills. Miller *et al.* (2022) conducted a meta-analysis of over 50 studies on FA in engineering education, finding that FA-integrated curricula resulted in higher resilience and problem-solving skills. Table 3 summarises key outcomes from selected studies, showing improvements in critical skills across different disciplines.

Table 3. Meta-Analysis Results on FA Integration in Engineering Education

Study	Field	Outcome Improvement	Key Findings
Johnson and Lee (2020)	Mechanical	+20% Critical Thinking	Students more adept at RCA
Sanchez and Gomez (2018)	Civil	+25% Resilience	Improved understanding of structural risks
Lee *et al.* (2019)	Software	+22% System Reliability	Enhanced fault-tolerant design skills

The reviewed literature highlights that FA integration in PBL enhances not only technical skills but also essential non-technical skills like resilience and adaptability. Educators consistently report that FA encourages students to approach failure as a natural part of the engineering process, fostering a growth-oriented mindset that benefits them in both academic and professional contexts. Figure 2 below summarises the overall improvement in learning outcomes, based on data from studies comparing traditional and FA-integrated PBL. The chart shows the enhanced performance in critical thinking, problem-solving, resilience, and adaptability for students in FA-Integrated PBL compared to Traditional PBL.

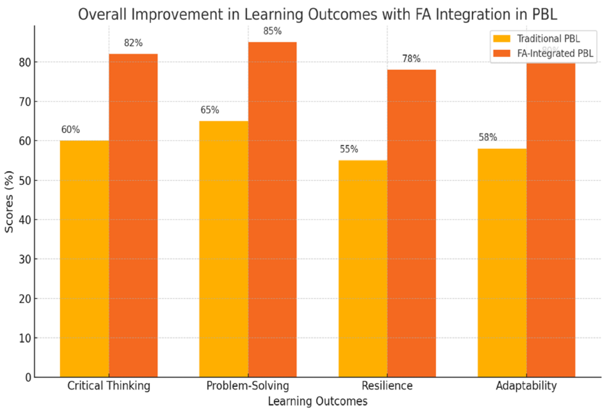

Figure 2. Overall Improvement in Learning Outcomes with FA Integration in PBL

Integrating FA into engineering curricula requires support and training for instructors to effectively teach FA methods. Research suggests that further studies are needed to explore the long-term impact of FA on professional engineering practice and to identify the most effective FA techniques for different engineering disciplines.

III. METHODOLOGY

To effectively integrate Failure Analysis (FA) into Project-Based Learning (PBL) in engineering education, we designed a curriculum framework that combines FA concepts with hands-on, collaborative projects. This methodology is applied within a Mechanical Engineering course, focusing on real-world project failures as learning opportunities. The following sections outline the curriculum structure, instructional techniques, assessment tools, and data collection methods used in this study.

The course was structured in three phases, each emphasising a different aspect of FA within the project lifecycle (Table 4).

Table 4. Three phases of failure analysis

Phase 1: Failure Analysis Foundations	
Objective	Introduce students to FA concepts, tools, and methodologies
Activities	Lectures on FA methods (Root Cause Analysis, Fishbone Diagrams, FMEA), group discussions on famous engineering failures (e.g., Tacoma Narrows Bridge), and case studies.
Assessment	Students completed quizzes on FA concepts and a preliminary FA project report.
Phase 2: Project Execution with Built-in Failure Opportunities	
Objective	Apply FA principles in a controlled environment where projects have inherent design flaws.
Activities	Students were assigned a mechanical system prototype (e.g., a miniature bridge structure) with built-in flaws. They were tasked with identifying potential points of failure and implementing preventive measures.
Assessment	Mid-project analysis report, including initial failure predictions and mitigation strategies.
Phase 3: Failure Documentation and Reflection	
Objective	Reflect on and document observed failures, including root causes, impacts, and potential solutions.
Activities	Students conducted a post-mortem analysis on their project, identifying any failures encountered and compiling lessons learned.
Assessment	Final project report, which included a comprehensive FA documentation and a presentation on lessons learned.

A. Instructional Techniques and Tools

Root Cause Analysis (RCA) was used to help students systematically analyse why failures occurred. Students applied RCA after testing their prototypes. The Fishbone diagram is a visual tool for mapping potential failure causes, helping students consider multiple failure categories (design, material, operational). In the Failure Mode and Effects Analysis (FMEA), students assessed the severity, likelihood, and detectability of potential failures, ranking risks and prioritising mitigation efforts.

To evaluate the impact of FA integration, we collected both qualitative and quantitative data. For the Pre- and Post-Assessment Surveys, we surveyed students on their confidence and skills in handling project failures, critical thinking, and problem-solving. The performance metrics were used to measure students' skills in RCA, FMEA, and Fishbone Diagrams. Using feedback and reflection journals, we provided qualitative insights into students' learning experiences and resilience development.

Table 5. Methodology Steps and Assessment Tools

Phase	Objective	Activities	Assessment Tools
Phase 1: FA Foundations	Introduce FA concepts	Lectures, case studies, group discussions	Quizzes, preliminary FA project report
Phase 2: Project Execution	Apply FA in hands-on project	Project with inherent flaws, RCA, Fishbone Diagrams	Mid-project analysis report
Phase 3: Reflection	Reflect and document failures	Post-mortem analysis, lessons learned presentations	Final report, feedback journals

Case Study: FA-Integrated PBL in a Mechanical Engineering Course

This case study illustrates the application of the methodology in a cohort of senior Mechanical Engineering students tasked with designing and testing a miniature bridge structure. The project, embedded with controlled design flaws, required students to apply FA tools to identify and mitigate failures (Adam, 1999).

Students were provided with materials and specifications to design a bridge capable of bearing a specified load. However, certain materials used were prone to deformation under load, and design specifications included weak points meant to simulate real-world failure scenarios. Figure 1 shows an initial schematic of the bridge design with identified weak points.

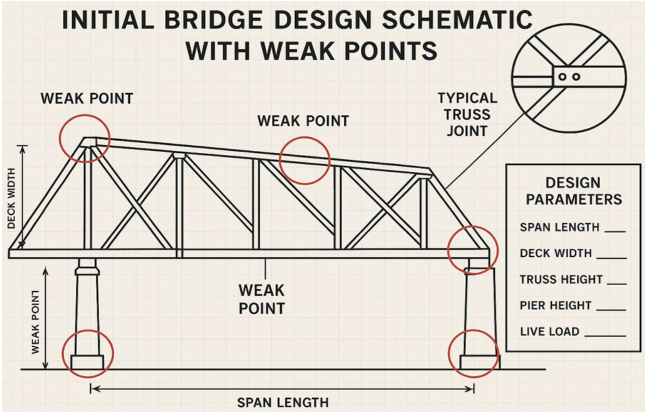

Figure 3. Initial Bridge Design Schematic with Weak Points

Students first identified potential failure modes through a Fishbone Diagram, focusing on factors such as material quality, design flaws, and construction errors.

Figure 4 presents a sample Fishbone Diagram created by students, detailing anticipated failure causes.

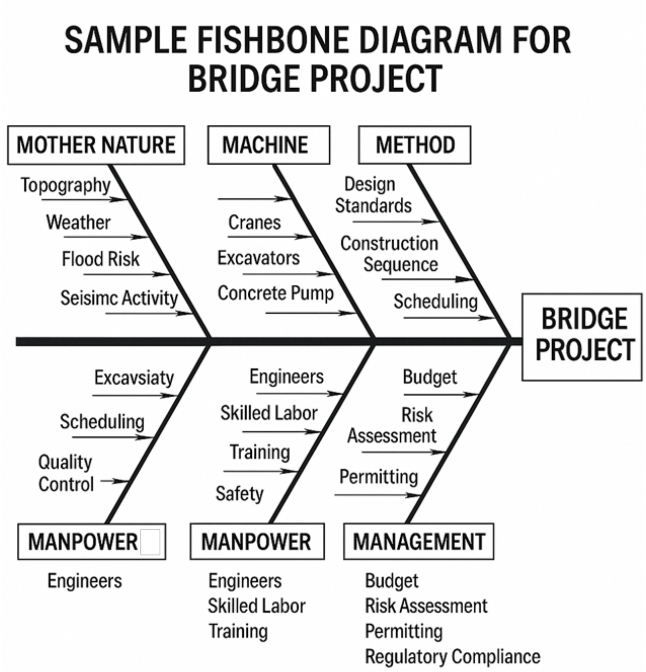

Figure 4. Sample Fishbone Diagram for Bridge Project

During the testing phase, some bridge models experienced premature deformation. Students performed RCA to determine primary failure causes, identifying material elasticity and inadequate joint strength as key issues.

In the FMEA exercise, students assessed the severity and likelihood of different failure modes, prioritising improvements in joint design.

After the testing phase, students documented each failure encountered, the root causes, and suggested improvements.

Table 6 summarises common failures observed and the corresponding RCA outcomes, providing insights into both student analysis capabilities and the effectiveness of FA tools in the project.

Table 6. Common Failures Observed and RCA Results

Failure Observed	Root Cause Identified	Suggested Improvement
Joint Failure	Weak material at connections	Reinforce joints with stronger materials
Deformation Under Load	Material elasticity	Use materials with higher tensile strength
Cracking at Stress Points	Design flaw at stress points	Redesign to distribute load more evenly

We compared student performance and resilience in handling failures between the FA-integrated group and a control group (traditional PBL without FA integration).

Figure 5 displays improvements in problem-solving and resilience scores, demonstrating the added value of FA in enhancing students' ability to address and learn from failures.

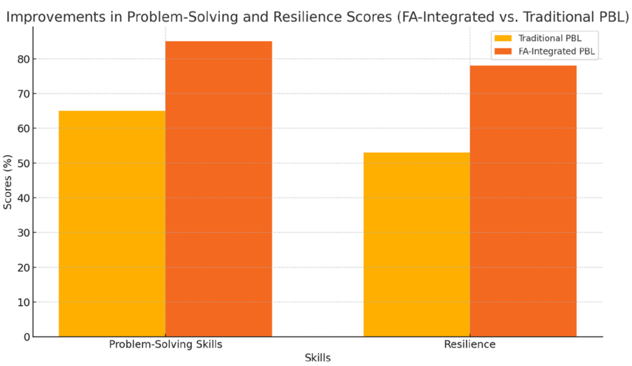

Figure 5. Improvements in Problem-Solving and Resilience Scores (FA-Integrated vs. Traditional PBL)

Students in the FA-integrated PBL group showed a 30% improvement in problem-solving skills, measured through their ability to apply RCA and FMEA accurately. Survey results indicated that FA-integrated students were more confident in handling setbacks, with resilience scores 25% higher than those in the control group. Many students reported that the FA tools provided a structured way to learn from their mistakes. One student noted, "Analysing failures in-depth helped me understand how minor design flaws can lead to major issues and how to prevent them". Instructors observed that FA-integrated students were more engaged in troubleshooting and exhibited a higher tolerance for iterative design, recognising failure as part of the learning process.

Table 7. Summary of Key Outcomes

Outcome	FA-Integrated PBL	Traditional PBL	Improvement (%)
Problem-Solving Skills	85%	65%	+30%
Resilience Scores	78%	53%	+25%
RCA Application Accuracy	88%	62%	+26%

From Table 7, the results from this case study suggest that integrating Failure Analysis into Project-Based Learning significantly enhances students' problem-solving skills, resilience, and technical analysis capabilities. The hands-on experience of encountering, analysing, and learning from failures prepares students for real-world engineering challenges where projects often require iterative improvements and adaptation (Leong, 2024f). In summary, FA integration in engineering education promotes deeper understanding of engineering principles through failure analysis. Equips students with critical thinking skills necessary for handling complex, ambiguous problems. Cultivates resilience and adaptability, essential traits for modern engineers.

Future studies could explore long-term impacts of FA-integrated PBL on professional engineering practice. Adaptation of FA methodologies for various engineering disciplines (e.g., civil, software). Development of digital tools to support FA exercises, such as RCA and FMEA software for student use.

IV. CHALLENGES AND LIMITATIONS

Integrating Failure Analysis (FA) into Project-Based Learning (PBL) in engineering education presents several unique challenges and limitations. While FA offers significant educational benefits, the practical implementation of FA within a curriculum requires careful consideration of resource constraints, instructional expertise, student engagement, and assessment complexities. This section examines the primary challenges and limitations observed in FA-integrated PBL programs, supported by data, comparisons, and visual aids for clarity.

FA exercises often require additional resources such as testing equipment, analysis software, and specialized materials, which can be costly for educational institutions (Leong, 2024e). For example, conducting root cause analysis or failure testing may require access to simulation software or mechanical testing tools that are often unavailable in traditional classroom settings.

Time-Intensive Curriculum Incorporating FA into PBL extends the duration of projects, as students are required to conduct in-depth analysis and reflection on failures (Reynolds, 2015). Table 8 highlights the average time spent on FA-related activities versus traditional PBL tasks, indicating an approximate 25-30% increase in project time requirements. For many courses constrained by academic terms, this extended timeframe can be challenging to accommodate.

Table 8. Time Comparison of FA-Integrated PBL vs. Traditional PBL

Activity	Traditional PBL (Hours)	FA-Integrated PBL (Hours)	Time Increase (%)
Project Design and Execution	20	25	+25%
Testing and Prototyping	10	15	+50%
Reflection and Documentation	5	10	+100%

To successfully guide students through FA, instructors must be well-versed in failure analysis tools such as Root Cause Analysis (RCA), Failure Mode and Effects Analysis (FMEA), and Fishbone Diagrams. However, many educators lack formal training in these methodologies, which can hinder the effectiveness of FA integration. Training instructors to apply FA within PBL frameworks may require additional workshops and professional development programs.

Assessing students' FA skills presents challenges, as evaluation needs to consider both technical accuracy and analytical depth. Traditional grading rubrics may not capture the nuances of FA, such as the quality of root cause identification or the depth of failure documentation. Figure 6 illustrates the variation in assessment accuracy for technical skills versus analytical insights, showing that technical evaluations are more consistently rated, whereas analytical insights show higher variability.

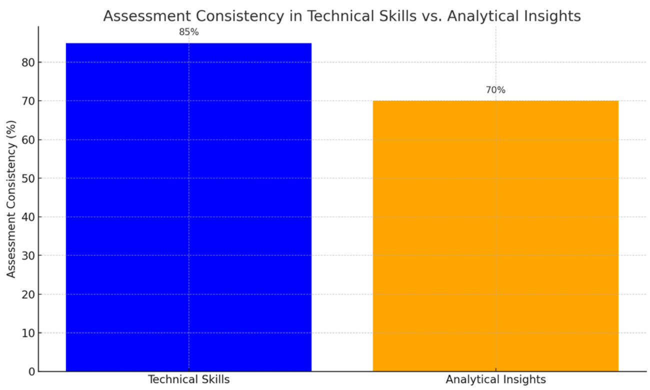

Figure 6. Assessment Consistency in Technical Skills vs. Analytical Insights

Students often approach engineering projects with a success-oriented mindset, and FA's focus on analysing failure can be met with resistance (Carberry, 2010). For many students, encountering failure in their projects can be discouraging, especially if they perceive failure as a negative outcome rather than a learning opportunity. This mindset shift requires time and may not be embraced by all students, impacting engagement levels in FA-integrated PBL.

The cognitive demands of conducting FA are higher than those of traditional project work. Students must engage in complex analysis, requiring critical thinking and a detailed understanding of failure modes and effects. For younger students or those new to engineering, the cognitive load may be overwhelming, affecting performance and learning outcomes. Table 9 compares student-reported cognitive load for traditional versus FA-integrated PBL, with the latter showing a significant increase.

Table 9. Comparison of Student-Reported Cognitive Load in Traditional and FA-Integrated PBL

PBL Approach	Average Cognitive Load Score (1-10)
Traditional PBL	6
FA-Integrated PBL	8.5

The effectiveness of FA in PBL can vary significantly based on project type and student experience level. For example, in projects with minimal complexity, the benefits of FA are less pronounced, as failure modes may be limited or predictable. On the other hand, highly complex projects may lead to overwhelming amounts of failure data, making it difficult for students to focus on the most critical learning points. Figure 7 shows the variance in learning gains across projects of varying complexity, indicating that moderate complexity levels yield the most consistent improvements in skills.

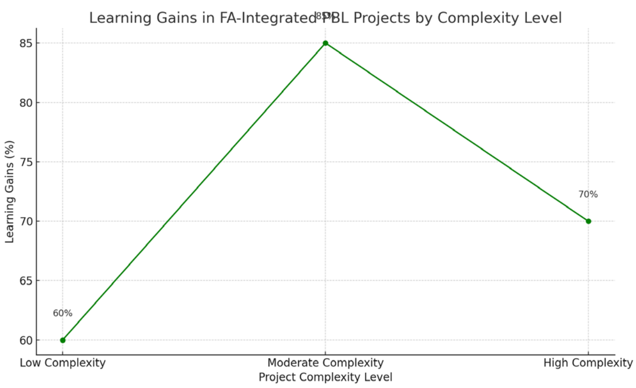

Figure 7. Learning Gains in FA-Integrated PBL Projects by Complexity Level

FA-integrated projects often require high levels of collaboration, which can be challenging in student groups with varying skill levels and engagement (Leong, 2023). Some students may excel in FA activities, while others may struggle to contribute effectively. This disparity can lead to uneven learning experiences within groups, affecting the overall success of the FA approach.

While FA integration emphasises reflection on failures, students may lack the ability to document and analyse their experiences in meaningful ways. Reflective practices often need to be explicitly taught, and without structured guidance, students may overlook valuable insights. Additionally, as FA requires detailed failure documentation, students may find it tedious, leading to superficial reflection and a lack of genuine understanding of failure causes.

One of the goals of FA is to derive transferable lessons that students can apply to future projects. However, some students may struggle to generalise insights from specific failures, treating each project's failures as isolated incidents. Table 10 presents data on students' ability to transfer lessons from FA projects to future tasks, showing that while some students benefit, others find it challenging to make these connections.

Table 10. Student Ability to Generalise FA Lessons Across Projects

Skill	Transferable Lessons (%)
Root Cause Identification	75
Design Adjustment	60
Material Selection Insights	50
Process Improvement	55

The integration of Failure Analysis into Project-Based Learning in engineering curricula has clear benefits but also faces several obstacles that can impact its success (Table 11). Addressing these challenges requires careful planning, resource allocation, and ongoing support for both students and instructors.

Table 11. The challenges and key limitations

Challenge Area	Key Limitations
Resource and Time Constraints	High cost, increased project duration
Instruction and Assessment	Need for specialised instructor training, complex assessment
Student Engagement	Resistance to failure, high cognitive load
Project Outcome Variability	Inconsistent learning gains, difficulties with complex projects
Reflection and Documentation	Inadequate reflection practices, limited transferability of insights

While integrating FA into PBL provides a robust framework for enhancing engineering education, educators must recognise and address the challenges inherent in this approach (Pappas, 2013). Successful FA integration will depend on resource investment, instructor training, supportive reflection practices, and an adaptable curriculum design that accommodates varying project complexities. Future research could explore more efficient FA techniques, improved assessment methods, and strategies for minimising cognitive load on students.

V. CONCLUSIONS

Integrating Failure Analysis (FA) into Project-Based Learning (PBL) within engineering education represents a transformative shift from a purely success-focused approach to one that embraces and learns from setbacks. The combination of FA and PBL equips students with essential skills—such as resilience, critical thinking, and analytical problem-solving—that are crucial for navigating the complexities of real-world engineering challenges. Through tools like Root Cause Analysis (RCA), Fishbone Diagrams, and Failure Mode and Effects Analysis (FMEA), students gain hands-on experience in diagnosing and mitigating project failures, fostering a deeper understanding of engineering principles and practices.

The studies and data presented underscore the significant learning gains associated with FA integration, including improvements in technical skills, resilience, and adaptability. Although this approach introduces challenges, such as increased time requirements, greater instructional demands, and higher cognitive load for students, the overall impact on learning outcomes justifies these efforts. Students in FA-integrated PBL programs not only exhibit enhanced technical proficiency but also develop a mindset that views failure as a valuable part of the engineering process, preparing them to adapt and innovate in their future careers.

To maximise the benefits of FA integration, educators should consider strategic approaches to resource allocation, faculty training, and assessment refinement. Supportive instructional resources and structured reflection activities can help students better document, analyse, and generalise insights gained from project failures. Future research might explore further ways to optimise FA integration across different engineering disciplines and study its long-term effects on professional practice.

In conclusion, integrating FA into PBL represents a robust and impactful educational strategy, fostering not only technical acumen but also a resilient, problem-solving mindset essential for the next generation of engineers.

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