

# The Effect of Project-Based Learning on Critical Thinking Skills in Structural Engineering Courses: A Meta-analysis Study

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## ABSTRACT

*This study aims to determine the influence of project-based learning on critical thinking skills in the Structural Engineering Course. This type of research is a meta-analysis research. The data sources in this study come from 13 national and international journals published in 2022-2025. Research data was obtained through the Mendeley database; Google Scholar; IEEE; and Scencedirect. The data collection technique is direct observation through the database. Data analysis is statistical analysis with the help of the JASP application. The results of this study concluded that there was a significant influence of the project-based learning model on critical thinking skills in the Structural Engineering course with a high value of ( $d = 0.823$ ;  $z = 7.826$ ;  $p < 0.001$ ) in the effect size category. This finding provides important information for lecturers to encourage students' critical thinking skills in civil engineering lectures.*

## ABSTRAK

Penelitian ini bertujuan untuk mengetahui pengaruh project based learning terhadap kemampuan berpikir kritis dalam Mata Kuliah Teknik Struktural. Jenis penelitian ini adalah penelitian meta-analisis. Sumber data dalam penelitian ini berasal dari 13 jurnal nasional dan internasional terbit tahun 2022-2025. Data penelitian diperoleh melalui database Mendeley; google scholar; IEEE; dan Scencedirect. Teknik pengumpulan data adalah observasi langsung melalui database. Analisis data adalah analisis statistik dengan bantuan aplikasi JASP. Hasil penelitian ini menyimpulkan bahwa adanya pengaruh signifikan model *project based learning* terhadap kemampuan berpikir kritis dalam mata kuliah Teknik Struktural dengan nilai ( $d = 0.823$ ;  $z = 7.826$ ;  $p < 0.001$ ) kategori effect size yang tinggi. Temuan ini memberikan informasi penting bagi dosen untuk mendorong kemampuan berpikir kritis siswa dalam perkuliahan Teknik sipil.

## 1. Introduction

Critical thinking skills are an irreplaceable foundation for civil engineering students Zulyusri et al., 2023). In designing building structures, a student is required to be able to analyze various complex variables, such as loads, materials, and environmental conditions, and evaluate various potential solutions (Bédard et al., 2012). Critical thinking skills enable an engineer to identify the assumptions underlying calculations, evaluate risks, and make the right decisions based on available

data and information ( Nurtamam et al., 2023; Luciana et al., 2024; Wantu et al., 2024). In addition, in facing unique and unexpected design challenges, critical thinking skills enable students to develop innovative and creative solutions (Joo et al., 2019).

The complexity of modern structural engineering problems further amplifies the necessity for advanced critical thinking skills. Projects increasingly involve multidisciplinary collaboration, integrating advancements in smart

materials, computational modeling, and green technologies (Haiying & Ya, 2016). For example, optimizing a high-rise building's energy efficiency while ensuring seismic resistance involves analyzing conflicting parameters, such as thermal performance versus structural rigidity (Fadilla et al., 2021); . Critical thinking enables engineers to deconstruct these multifaceted issues, prioritize variables, and validate solutions through iterative testing and evidence-based reasoning. Moreover, the rise of Building Information Modeling (BIM) and artificial intelligence in structural analysis necessitates engineers to critically interpret algorithmic outputs and challenge potential biases or oversimplifications in automated systems (Naji et al., 2020). In educational settings, fostering these skills prepares future engineers to navigate uncertainties in real-world scenarios, such as retrofitting aging infrastructure or addressing resource scarcity in developing regions. Ultimately, cultivating critical thinking is not merely an academic exercise but a professional imperative, ensuring engineers can innovate responsibly and uphold societal trust in the built environment (Haiying & Ya, 2016).

Engineering students face a variety of challenges in developing critical thinking skills, which are fundamental aspects of problem-solving and decision-making in engineering (Gavin, 2011). One of the main challenges is the learning approach that is still dominated by conventional methods, such as lectures and practice questions that are oriented towards a single answer. This method tends to limit the exploration of more in-depth concepts and encourages students to evaluate various alternative solutions (Ahern et al., 2019). In addition, engineering curricula that are packed with theoretical material often leave little room for students to engage in critical discussions, reflection, and in-depth problem analysis. As a result, they are more trained in applying existing formulas and methods than developing creative analytical thinking in the face of real challenges in the field of engineering (Sumarni & Kadarwati, 2020; Ali et al., 2024; Oktarina et al., 2018); (Zulkifli et al., 2022).

In addition to the learning approach, another factor that contributes to students' difficulties in critical thinking is the lack of involvement in real-life problem-based projects (Anazifa & Djukri, 2017; Wu & Hyatt, 2016). Many college students do not have enough opportunities to deal with complex real-world scenarios, where they have to consider various variables and make decisions based on careful analysis. The lack of hands-on

experience in identifying, formulating, and evaluating engineering solutions makes students tend to rely on mechanistic approaches in completing their academic assignments (Sari & Prasetyo, 2021). In addition, high academic pressure, with tight deadlines and heavy workload, often hinders students from developing reflective and analytical thinking habits. Therefore, more innovative learning strategies, such as Project-Based Learning (PBL), are needed, which can provide a conducive environment for students to hone critical thinking skills through hands-on experience in solving complex engineering problems (Rehman et al., 2024; Lou et al., 2017).

Project-Based Learning (PBL) is an innovative learning model that emphasizes the active involvement of students in the learning process through the completion of real projects relevant to their field of study (Septiadevana & Abdullah\*, 2024). In contrast to conventional methods that are instructional and oriented to one-way knowledge transfer, PBL encourages students to explore concepts, integrate theory with practice, and develop problem-solving skills through hands-on experience (Sari & Prasetyo, 2021). In engineering education, the application of PBL generally involves the design and implementation of engineering challenge-based projects that mimic real-world situations, such as building structure design, materials testing, or engineering system development. Through this approach, students not only gain a deeper understanding of engineering concepts, but also hone their skills in analytical thinking, teamwork, and effectively manage resources and time (Anazifa & Djukri, 2017).

PBL has great potential in improving students' critical thinking skills, especially in the context of engineering education that demands data-driven analysis and decision-making skills (Hansen, 2009). By facing real challenges, students are forced to identify problems, evaluate various alternative solutions, and consider the technical and economic implications of the decisions taken. In addition, PBL encourages students to develop reflective skills by actively evaluating their work processes, identifying mistakes, and finding more optimal solutions (Fadilla et al., 2021 ; Elfira & Santosa, 2023). Collaborative interaction in PBL also plays a crucial role in building evidence-based communication and argumentation skills, which are crucial aspects in the development of critical thinking (Li & Zhu, 2020). Thus, the implementation of PBL in engineering education not only improves conceptual understanding, but

also equips students with high-level thinking skills that are essential in facing challenges in the professional world (Septiadevana & Abdullah 2024)

Research conducted by Prince and Felder (2006) shows that active learning approaches, including PBL, significantly improve engineering students' conceptual understanding as well as analytical skills compared to conventional learning methods. A meta-analysis study conducted by Freeman et al. (2014) also found that students who learn using active methods, such as PBL, have a higher rate of academic success compared to students who rely solely on traditional lecture methods. The results of this study reinforce the argument that PBL can create a more dynamic learning environment, where students are encouraged to explore various perspectives and develop creative solutions to complex engineering problems.

Furthermore, research by Mills and Treagust (2003) in the civil engineering program shows that students who are involved in problem-based projects have better conceptual understanding as well as sharper analytical skills compared to students who only learn through theory. Similar research by Krajcik and Blumenfeld (2006) also confirms that PBL encourages students to think more reflectively and systematically in solving engineering problems. Thus, the results of this study confirm that PBL not only contributes to students' academic understanding but also improves high-level thinking skills that are needed in the industrial world and engineering professions.

Although various studies have shown the effectiveness of Project-Based Learning (PBL) in improving students' critical thinking skills, there are still some research gaps that need to be addressed. First, most previous studies have focused more on the application of PBL in education in general or in STEM fields at large, but there is still little research specifically examining its impact in structural engineering courses. Second, the results of existing research are often case studies or experiments on a limited scale, so they do not provide a broader picture of the effectiveness of PBL in various academic and geographical contexts. Third, although there are several meta-analyses related to project-based learning, there is still a lack of research that specifically examines the impact of PBL on the critical thinking skills of civil engineering and structural engineering students compared to conventional learning methods. Based on this hasl, this study aims to influence project-

based learning on critical thinking skills in the Structural Engineering Course.

## 2. Literature Review

### Problem Based Learning

Problem Based Learning (PBL) is a learning approach that emphasizes solving real problems as a means to improve students' understanding and skills (Hansen, 2009). In this model, students are invited to analyze, explore, and find solutions to a problem presented by the educator. Through this process, students not only gain theoretical knowledge, but also develop critical thinking, collaboration, and communication skills that are essential in the real world. PBL also provides opportunities for students to learn independently and be responsible for their learning process, thereby increasing their motivation and involvement in learning (Luciana, 2022; Wu & Hyatt, 2016). The implementation of PBL in the world of education has proven effective in improving the quality of learning at various levels. Based on contextual problems, this model helps students connect theory with practice, so that they can more easily understand the concepts being learned (Sari & Prasetyo, 2021). In addition, PBL also encourages metacognitive skills, namely the ability to manage and evaluate one's own thinking process. However, the success of PBL is highly dependent on the role of educators in designing appropriate problems, providing appropriate guidance, and creating a conducive learning environment. Therefore, the implementation of PBL requires a mature strategy in order to be able to produce an optimal learning experience for students.

### Critical Thinking

Critical thinking is a cognitive skill that allows someone to analyze, evaluate, and interpret information objectively before making a decision. In the world of education, critical thinking skills are very important because they help students not only receive information passively, but also question, compare, and construct logical arguments (Rehman et al., 2024). Critical thinking involves various aspects, such as the ability to identify patterns, recognize hidden assumptions, and test the validity of a statement based on available evidence. With these skills, individuals can develop a more rational and reflective way of thinking in facing various academic and daily life challenges (Fadilla et al., 2021).

The importance of critical thinking is increasing in the digital era, where information is widespread and often mixed with hoaxes or misinformation. Someone who has critical thinking skills can sort information more selectively, distinguish facts from opinions, and draw conclusions based on data and logic. In the context of learning, methods such as Problem Based Learning (PBL) and argumentation-based discussions can help hone students' critical thinking skills (Asnur et al., 2024). However, to develop critical thinking optimally, a learning environment is needed that encourages freedom of thought, curiosity, and the courage to express opinions logically and based on evidence.

### Structural Engineering

Structural engineering is a branch of civil engineering that focuses on the design, analysis, and construction of building structures to withstand external loads and forces acting on them (Ahern et al., 2019). This discipline plays an important role in ensuring the safety, stability, and resistance of a building to various factors, such as gravity loads, wind, earthquakes, and temperature changes. A structural engineer must understand the principles of material mechanics, structural dynamics, and design methods that comply with applicable safety standards and building regulations. With the development of technology, the use of structural analysis software and innovative materials, such as fiber reinforced polymer (FRP) and high-performance concrete, is increasingly helping to create efficient and sustainable designs (Lou et al., 2017)

In practice, structural engineering is not only applied to buildings, but also to bridges, tunnels, dams, and other infrastructure. The main challenge in this field is how to design structures that are not only strong and safe, but also economical and environmentally friendly. Therefore, research continues to develop in finding new materials and construction methods that are more efficient and sustainable (Ahern et al., 2019). In addition, with the increasing complexity of modern infrastructure needs, the role of technologies such as Building Information Modeling (BIM) and artificial intelligence (AI) is increasingly integrated into the design process and monitoring of structural performance. With a combination of engineering science, innovation, and strict regulations, structural engineering continues to contribute to creating safe and highly resilient infrastructure.

### 3. Methods

This type of research is a meta-analysis research. The data sources in this study come from 13 national and international journals published in 2022-2025. Meta-analysis is carried out by collecting, filtering, and analyzing the results of empirical research that have been published in scientific journals and indexed conference proceedings (Tamur et al., 2020). Studies included in the analysis must meet certain inclusion criteria, such as the use of PBL methods in structural engineering learning, the measurement of critical thinking skills as a dependent variable, and the presentation of quantitative data that allows the calculation of effect size. Data sources were obtained from academic databases such as Mendeley; google scholar; IEEE; dan Scencedirect. using relevant keywords, such as Project-Based Learning, critical thinking skills, engineering education, and structural engineering courses.

Data analysis was carried out by calculating the effect size of each study that met the inclusion criteria, using appropriate statistical models, such as fixed-effects models or random-effects models, depending on the level of heterogeneity of the data. Heterogeneity between studies was tested using Cochran's Q test and  $I^2$  statistics to determine whether there was significant variability among the study results. In addition, a moderator analysis was carried out to explore factors that can affect the effectiveness of PBL, such as differences in students' education levels, types of projects applied, and methods of evaluating critical thinking skills. To overcome potential publication bias, funnel plot analysis and Egger's regression test were used to ensure that the results of the study were not affected by limitations in the publication of the study. With this approach, this study is expected to provide a strong evidence-based synthesis of the impact of PBL on critical thinking skills in structural engineering education. Selanjutnya, kriteria nilai effect size dalam penelitian dapat dilihat pada Tabel 1.

**Table 1.** Category Effect Size Value

Effect Size	Category
$0.0 \leq ES \leq 0.2$	Low
$0.2 \leq ES \leq 0.8$	Medium
$ES \geq 0.8$	High

Source: (Borenstein et al., 2007; Bachtiar et al., 2023; Tamur et al., 2020)

### 4. Result

Based on the results of data search through the database, 13 studies/articles met the inclusion criteria. The effect size and error standard can be seen in Table 2.

**Table 2.** Effect Size and Standard Error Every Research

Code Journal	Years	Effect Size	Standard Error
R1	2022	0.88	0.29
R2	2025	0.72	0.18
R3	2025	0.66	0.30
R4	2023	1.30	0.35
R5	2024	1.02	0.23
R6	2024	0.91	0.38
R7	2025	0.44	0.20
R8	2024	0.29	0.19
R9	2022	1.92	0.39
R10	2023	0.75	0.40
R11	2024	0.61	0.20
R12	2024	0.96	0.26
R13	2025	1.19	0.33

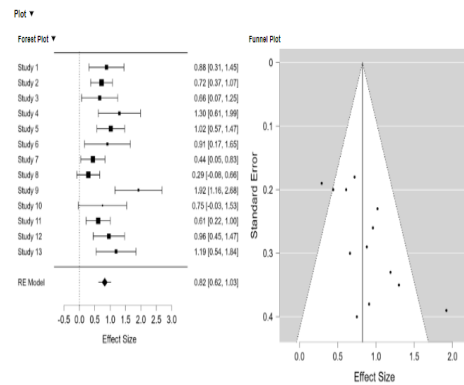
Based on Table 2, the effect size value of the 13 studies ranged from 0.49 to 2.91. According to Borenstein et al., (2007) Of the 13 effect sizes, 6 studies had medium criteria effect sizes and 7 studies had high criteria effect size values. Furthermore, 13 studies were analyzed to determine an estimation model to calculate the mean effect size. The analysis of the fixed and random effect model estimation models can be seen in Table 3.

**Table 3.** Fixed and Random effect

	Q	df	p
Omnibus test of Coefficients Model	61.224	1	< 0.001
Test of Residual Heterogeneity	24.254	12	< 0.001

Based on Table 3, a Q value of 61.224 was obtained higher than the value of 24.254 with a coefficient interval of 95% and a p value of 0.001 <. The findings can be concluded that the value of 24 effect sizes analyzed is heterogeneously distributed. Therefore, the model used to calculate the mean effect size is a random effect model. Furthermore, checking publication bias through funnel plot analysis and Rosenthal fail safe N (FSN) test (Tamur et al., 2020; Badawi et al., 2022; Ichsan et al., 2023b; Borenstein et al., 2007). The results of

checking publication bias with funnel plot can be seen in Figure 2.



**Figure 2.** Funnel Plot and Forest Plot

Based on Figure 2, the analysis of the funnel plot is not yet known whether it is symmetrical or asymmetrical, so it is necessary to conduct a Rosenthal Fail Safe N (FSN) test dan Eggers' s test. The results of the Rosenthal Fail Safe N calculation can be seen in Table 4.

**Table 4.** Fail Safe N

File Analysis	Drawer	Target	Observed
	Fail Safe N	Significance	Significance
<b>Rosenthal</b>	598	0.050	< 0.001

**Table 5.** Uji Eggers's

	z	p
<b>Sei</b>	3.218	< 0.001

Based on Table 4 dan 5 , the Fail Safe N value of 598 is greater than the value of  $5k + 10 = 5(10) + 10 = 60$  And the results of Egger's test have a p value of < 0.001. so it can be concluded that the analysis of 13 effect sizes in this data is not biased by publication and can be scientifically accounted for. Next, calculate the p-value to test the hypothesis through the random effect model. The results of the summary effect model analysis with the random effect model can be seen in Table 7.

**Tabel 7.** Summary/ Mean Effect Size

Coefficient	Effect Size	Standard Error	z	p
<b>Intercept</b>	0.823	0.105	7.826	< 0.01

Table 7, the summary effect size value is 0.823 and the standard error is 0.105. This finding explains the influence of the project-based learning influence model on critical thinking skills in the Structural Engineering Course compared to the conventional model ( $z = 7.826$  ;  $p < 0.001$ ) in the high effect size category. Students who learn using the PBL approach tend to be better able to identify, analyze, and evaluate engineering solutions compared to those who use traditional learning methods (Sumarni & Kadarwati, 2020). This is due to the nature of PBL which encourages discussion, collaboration, and exploration of various alternative solutions to a structural problem. Additionally, students involved in projects tend to be more active in asking questions and testing hypotheses, which is a key component of critical thinking (Wu & Hyatt, 2016; Sari & Prasetyo, 2021).

The effectiveness of PBL in improving critical thinking skills is also influenced by several factors, such as project design, instructor involvement, and the level of complexity of the assigned task. Studies show that projects designed with the appropriate level of complexity are more effective in stimulating critical thinking compared to projects that are too simple or too complicated (ULUM, 2022). In addition, the role of the instructor in providing guidance and feedback is essential to ensure that students truly understand the concepts learned and are able to relate them to real challenges in structural engineering (Ichsan et al., 2023). In addition, not all students have the same level of readiness in facing project-based learning, so strategies that can accommodate individual differences are needed. Several studies also highlight the need for technology integration in PBL to improve learning effectiveness, such as the use of engineering simulation software or BIM (Building Information Modeling) technology.

PBL is an effective approach in improving students' critical thinking skills in the field of structural engineering (Anazifa & Djukri, 2017). With the right design and adequate support from instructors, PBL can provide a richer learning experience and relevant to the challenges of the industrial world. Therefore, higher education institutions are advised to adopt PBL as the primary method in teaching structural engineering, while still considering the factors that can affect its success (Sari & Prasetyo, 2021).

## Discussion

This is due to the nature of PBL which encourages discussion, collaboration, and exploration of various alternative solutions to a structural problem. Additionally, students involved in projects tend to be more active in asking questions and testing hypotheses, which is a key component of critical thinking (Wu & Hyatt, 2016; Sari & Prasetyo, 2021).

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## 5. Conclusion

From the results of this study, it can be concluded that there is a significant influence of the project-based learning model on critical thinking skills in the Structural Engineering course with a high value ( $d = 0.823$ ;  $z = 9.926$ ;  $p < 0.001$ ) in the effect size category. This finding provides important information for lecturers to encourage students' critical thinking skills in civil engineering lectures.

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