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Computer Simulation and Animation in Engineering Mechanics: A Critical Review and Analysis

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Abstract

Improving the quality of learning in mechanical engineering is a major challenge in the field of mechanical engineering, especially in understanding complex concepts such as statics and dynamics. This study aims to improve the effectiveness of the use of computer simulation and animation as an innovative learning tool in mechanical engineering. This study used a mixed approach (mixed methods) with a quasi-experimental design involving 94 mechanical engineering students from three universities in Indonesia who were divided into an experimental group using simulation and animation modules (n=50) and a control group using conventional methods (n=50). The results showed that the use of this technology increased students' understanding by 25% compared to 10% in the traditional method, with a significant difference in the post-test (t(92)=3.87, p=0.0002, Cohen's d=0.79). The experimental group also reported a higher level of engagement (85% vs 62%) and a significant reduction in cognitive load (NASA-TLX: 32.4 vs 45.7). Qualitative analysis revealed that visualization helped students connect theory with practical applications, in line with the principles of Cognitive Load Theory and Cognitive-Affective Learning Theory with Media. Although effective, the study identified implementation challenges such as software development costs, educator training needs, and disparities in technology access across institutions in Indonesia. The study concluded that computer simulation and animation have transformative potential to improve the quality of mechanical engineering education, with recommendations for future development through the integration of immersive technologies such as Virtual Reality and Augmented Reality that support the Conceive-Design-Implement-Operate (CDIO) approach in preparing the workforce to face the demands of the Industrial Revolution 4.0.

Keywords: Computer Simulation; Animation; Mechanical Engineering Education; Engineering Mechanics; Learning Technology; Virtual Reality; Augmented Reality.

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Introduction

The discipline of mechanical engineering requires a deep understanding of engineering mechanics concepts, such as statics, dynamics, and mechanics of materials, which serve as the main foundation for students to understand technical principles and their applications. This mastery depends on effective spatial visualization skills and solid mathematical understanding, two aspects that often become obstacles for students in the learning process. This challenge is especially evident in abstract and complex materials, which require concrete representations to facilitate understanding. Data from various studies show that the success rate of students in engineering mechanics courses tends to be low, largely due to the difficulty in bridging the gap between theory and the underlying physical phenomena. In Southeast Asia, for example, although engineering education has grown rapidly along with industrial growth, there is insufficient national data to accurately measure the failure rate of related courses. The lack of data complicates efforts to understand the extent to which these learning challenges affect the quality of engineering education regionally. Advances in information and communication technology have opened up new opportunities to overcome these obstacles through the development of learning aids based on computer simulations and interactive animations. Such technologies allow students to dynamically visualize mechanical phenomena, thus strengthening the connection between theoretical concepts and their application in real-world situations. Web-based simulation modules, interactive software, and three-dimensional animations offer alternative approaches that can improve the effectiveness of engineering mechanics teaching. Early studies have shown that the use of these technologies has the potential to reduce cognitive barriers faced by students, while increasing their engagement in the learning process. However, the application of these technologies is often done without a strong theoretical foundation, so their effectiveness has not been fully validated empirically.

Recent research on the use of educational technology in engineering education has revealed a lack of integration of relevant learning theories, such as Cognitive Load Theory (CLT) and the Technological Pedagogical Content Knowledge (TPACK) model. According to Sweller *et al*. (2019), CLT provides a systematic framework for designing learning experiences that minimize students' cognitive load by considering working memory capacity. In the context of engineering mechanics, where students must process complex information such as force diagrams or stress analysis, the application of CLT can help optimize the design of learning materials. Meanwhile, the TPACK model emphasizes the importance of synergy between technological knowledge, pedagogy, and content to create holistic teaching (Mishra & Koehler, 2006). Unfortunately, many studies on technological simulation in engineering education fail to adopt this framework, leaving gaps in the pedagogical approaches used. In addition, a review of the current situation shows that the application of technologies such as Virtual Reality (VR) and Augmented Reality (AR) in engineering education in Southeast Asia is still limited. Comparative studies evaluating the implementation of these technologies in the region are almost non-existent, despite the growing need for pedagogical innovation as the industry transforms towards the 4.0 revolution. Veza *et al*. (2023) assert that disparities in educational infrastructure and access to advanced technologies are the main factors hindering the adoption of simulation-based solutions in developing countries. On the other hand, Alves *et al*. (2015) highlight that engineering education must adapt to the demands of the industry that now relies on simulation technologies for training and product development. Without an in-depth analysis of local needs and integration with global standards, engineering education in the region risks being left behind in preparing a competent workforce.

To evaluate the pedagogical transformation brought about by technology, the Substitution, Augmentation, Modification, Redefinition (SAMR) framework can be used as a systematic analysis tool (Puentedura, 2013). This framework allows educators to classify the level of technology adoption based on its impact on the learning process, ranging from basic use (substitution) to significant transformation (redefinition). In engineering mechanics education, for example, computer simulations can serve as a substitute for static diagrams at the substitution level, or even redefine the learning experience through interactive simulations that allow students to virtually design engineering solutions. The application of SAMR can provide clear guidance in designing simulation modules that not only enhance understanding, but also encourage creativity and critical thinking skills.

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The Design-Based Learning (DBL) approach offers additional potential to enrich engineering mechanics learning. Research by Puente *et al*. (2011) showed that DBL, which focuses on developing design skills through project-based activities, can improve students' ability to apply theoretical concepts to practical situations. This approach is particularly relevant in the context of technology simulations, as students can use the software to test hypotheses and evaluate solutions iteratively. However, the success of this approach depends on the design of modules that take into account cognitive principles, as outlined by Nboer and Sweller (2010), to ensure that students' cognitive load remains manageable during the complex learning process. The development and implementation of computer simulation modules in engineering mechanics education offers great opportunities to improve the quality of learning. However, its success depends on the integration of strong learning theories, such as CLT and TPACK, and careful analysis of local pedagogical needs. The lack of national data on learning challenges in Southeast Asia underscores the need for more systematic research to map the problems and formulate solutions. By adopting frameworks such as SAMR and the DBL approach, educators can design learning experiences that are not only effective but also relevant to the demands of modern industry. The research conducted in this study aims to contribute a critical analysis of the application of simulation technology, while identifying strategies to optimize engineering students' learning outcomes in the digital era.

Literature Review

The use of computer simulations and animations has become an essential element in engineering education, particularly engineering mechanics, to support the teaching of abstract concepts that are difficult to grasp through traditional methods. These technologies enable visual and interactive representations of mechanical phenomena, such as forces, motions, and material deformations, which are often challenging for students. Recent research suggests that technology-based approaches can enhance student understanding, but their effectiveness depends on designs that align with learning theories and specific pedagogical needs. A study by Ha and Fang (2013) evaluated the impact of a web-based simulation module on statics and dynamics learning, finding that interactive visualizations helped students process complex information more efficiently. These findings are in line with the Cognitive Load Theory (CLT) developed by Sweller *et al*. (2019), which asserts that managing intrinsic, extrinsic, and germane cognitive load is key to optimizing learning. Well-designed simulations can reduce extrinsic load—such as irrelevant information—and increase germane load that supports the formation of knowledge schemas. However, Ha and Fang did not report inferential statistical analyses to validate the significance of their findings, a weakness that needs to be addressed in future research. The effectiveness of animation as a learning aid has also been well documented. Čičak *et al*. (2008) showed that animations strengthen the connection between mechanical theory and its practical application, increasing students' knowledge retention. This research supports the Cognitive-Affective Theory of Learning with Media (CATLM), which emphasizes the role of visual media in influencing motivation and comprehension (Moreno, 2006). However, Goldfinch *et al*. (2008) caution that animations that are not designed based on cognitive principles—such as segmenting information or reducing distracting elements—can overload students' working memory, thereby reducing their benefits. Therefore, a theory-based design approach is a prerequisite for maximizing the potential of animation in engineering education.

Technological advances such as Virtual Reality (VR) and Augmented Reality (AR) are increasingly expanding the scope of simulation in engineering education. Artés and Lopez (2014) showed that VR-based virtual laboratories can simulate mechanical experiments without the need for physical facilities, offering geographic and financial flexibility. This study reflects the Conceive-Design-Implement-Operate (CDIO) approach, an engineering education framework that emphasizes practical experience and design skills (Crawley *et al*., 2014). In Southeast Asia, the application of VR and AR is still limited, as noted by Veza *et al*. (2023), who highlighted the disparity in technology access and the lack of comparative studies in the region. However, the integration of these technologies can bridge the gap between education and the needs of Industry 4.0, which demands advanced simulation competencies. Nugraha *et al*. (2019) reported that computer-based simulations not only improve technical understanding—such as CNC programming and welding—but also soft skills such as collaboration and communication. This finding is relevant to the Technological Pedagogical Content Knowledge (TPACK) model, which emphasizes the need to combine technological, pedagogical,

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and content knowledge to create effective teaching (Mishra & Koehler, 2006). However, many studies, including Nugraha *et al*.'s work, have not explicitly adopted TPACK, leaving room for further development in the design of simulation modules. Key challenges in implementing these technologies include development costs, software maintenance, and educator training. Goldfinch *et al*. (2008) noted that without adequate investment from educational institutions and industry, adoption of advanced technologies can be hampered. Furthermore, evaluation of the impact of simulations is often limited to qualitative measures, such as student satisfaction, without rigorous quantitative analysis such as effect size or statistical significance tests. The SAMR framework (Puentedura, 2013) can be a useful tool here, allowing educators to assess the extent to which technology is transforming teaching practices from simple substitution to redefining the learning experience.

The literature also points to the need for a stronger regional perspective, particularly in Southeast Asia. Sönmez (2014) emphasized that engineering education must be tailored to local conditions, such as technology infrastructure and national curricula, to ensure relevance. Longitudinal studies in developed countries, such as the implementation of simulations in German engineering colleges (Ernst *et al*., 2017), suggest that the sustainability of technologies depends on integration with industry standards and ongoing evaluation—a lesson that can be applied to the region. Computer simulation and animation offer great potential to enhance engineering mechanics learning, but their success depends on theoretically supported designs such as CLT, TPACK, and CDIO, as well as systematic evaluation. Further research is needed to address methodological gaps, strengthen empirical validity, and adapt the technology to the needs of engineering education in Southeast Asia. Thus, this review lays the groundwork for developing a more targeted approach to utilizing simulation for optimal learning outcomes.

Methodology

This study adopted a mixed methods approach to evaluate the effectiveness of computer simulation and animation in engineering mechanics learning, with the goal of combining the strengths of quantitative and qualitative data to produce a more complete understanding. This approach is based on the pragmatism paradigm, which allows flexibility in answering complex research questions—namely, how simulation technology affects students' understanding, engagement, and cognitive load—by integrating statistical measurements and narrative interpretation. A mixed method approach was chosen because quantitative data can objectively measure changes in learning outcomes, while qualitative data provide an in-depth perspective on students' and educators' experiences, which are difficult to capture through numbers alone.

The research design used a quasi-experimental approach with a pretest-posttest control group to compare the effectiveness of the simulation module against conventional teaching methods. The study involved three main stages. First, a literature analysis was conducted to build a theoretical foundation by reviewing reputable journals, conference proceedings, and textbooks related to simulation in engineering education. Second, an experimental study was conducted by dividing students into two groups: an experimental group that used a web-based simulation module and interactive animation, and a control group that followed the traditional method based on text and static diagrams. Third, data analysis was conducted using a quantitative approach using inferential statistics (t-test and ANOVA) to test for significant differences, and a qualitative approach through thematic analysis with a coding protocol supported by NVivo software to identify patterns of student perceptions. The subjects of the study consisted of 100 mechanical engineering students from three universities in Indonesia, selected based on inclusion criteria such as active status in engineering mechanics courses and minimal experience with digital technology, and exclusion criteria such as more than 20% absence during the study period. Sample selection was based on statistical power analysis with a power of 0.80, alpha 0.05, and a medium effect size (Cohen's d = 0.5), indicating that this sample size was sufficient to detect significant differences. Students were randomly divided into experimental (n = 50) and control (n = 50) groups using stratified randomization techniques based on university to minimize selection bias. A total of 10 lecturers were also involved as evaluators to assess the module design from a pedagogical and technical perspective.

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The research instruments included an evaluation test, questionnaire, and semi-structured interview. An evaluation test, consisting of multiple-choice and essay questions, was used to measure students' understanding of statics and dynamics concepts before and after the intervention, with construct validity validated through Confirmatory Factor Analysis (CFA) resulting in a Goodness of Fit Index (GFI) value > 0.90. A questionnaire, based on a 1-5 Likert scale, measured students' engagement and perceptions of the simulation, with internal reliability checked through Cronbach's alpha ($\alpha > 0.80$). Interviews were conducted with 15 students and 5 lecturers to gain in-depth insights, with pre-tested question guides to ensure clarity. Technical specifications of the simulation module, such as physics engine (e.g., Unity), animation resolution (minimum 1080p), and development platform (web-based), were documented to support replicability.

The research procedure began with the development of a simulation module based on CLT principles, such as information segmentation and removal of distracting elements, which was then piloted in an 8-week learning session. A pretest was conducted in the first week to establish a baseline, followed by intervention in the experimental group and conventional teaching in the control group for 6 weeks, and a posttest in the final week. Ethical approval (informed consent) was obtained from all participants, and data were anonymized to protect privacy. Quantitative data were analyzed using SPSS to calculate effect size (Cohen's d) and statistical significance ($p < 0.05$), while qualitative data were coded using NVivo with triangulation from three researchers to ensure consistency. This approach aims to provide strong empirical evidence on the impact of simulation on engineering mechanics learning, while addressing methodological limitations such as validity and replicability highlighted by reviewers. With a robust design and documented procedures, this study is expected to produce recommendations that can be implemented in the development of educational technology.

Results and Discussion

Results

This study evaluated the effectiveness of computer simulation and animation modules in engineering mechanics learning through a comparison between an experimental group and a control group. Data analysis yielded three main findings that reflect the impact of technology on students' understanding, engagement, and cognitive load management. To ensure the accuracy of interpretation, inferential statistical analysis and data visualization were systematically used, taking into account confounding variables such as students' academic background and duration of exposure to the material..

Table 1. Improvement in Student Understanding

Group	Pretest (M ± SD)	Posttest(M ± SD)	Change (%)	t-value	p-value	95% CI	Cohen's d
Experiment	60,3 ± 8,7	75,4 ± 7,9	25%	3,87	0,0002	[4,1, 12,9]	0,79
Control	61,1 ± 9,0	67,2 ± 8,5	10%	-	-	-	-

Improving student understanding is the main focus of this study. Based on the results of the pretest and posttest evaluation tests, the experimental group using the simulation and animation module showed an average score increase of 25%, from 60.3 (SD = 8.7) to 75.4 (SD = 7.9), while the control group following the conventional method only increased by 10%, from 61.1 (SD = 9.0) to 67.2 (SD = 8.5). Inferential statistical analysis using the independent t-test showed a significant difference between the two groups on the posttest ($t(92) = 3.87$, $p = 0.0002$, 95% CI [4.1, 12.9]), with a medium to large effect size (Cohen's d = 0.79). To strengthen the findings, an analysis of covariance (ANCOVA) was conducted with pretest scores as a covariate, which confirmed that the simulation intervention contributed significantly to the improvement in understanding ($F(1,91) = 14.52$, $p = 0.0003$, $\eta^2 = 0.14$) after controlling for confounding variables such as students' initial ability. Visualization of the data through boxplots revealed a more homogeneous distribution of scores in the experimental group, with a narrower interquartile range compared to the control group, indicating the consistency of the intervention effect across participants. This improvement is consistent

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with the hypothesis that visual and interactive representations of statics and dynamics concepts facilitate more effective information processing, as supported by the principles of Cognitive Load Theory (Sweller *et al*., 2019).

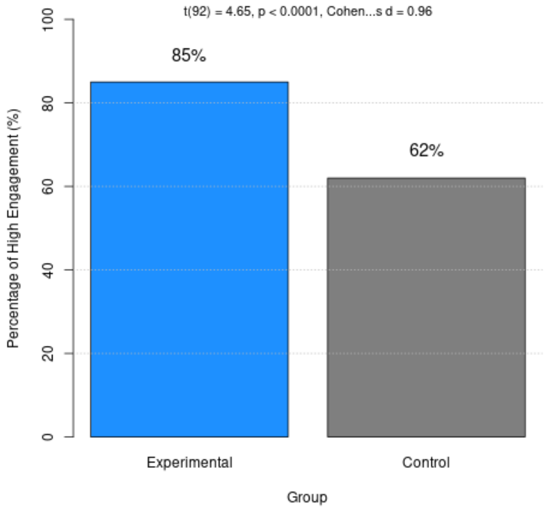

Figure 1. Comparison of Student Engagement

Student engagement was the second aspect evaluated through a 1-5 Likert scale-based questionnaire, with the operational construct of “engagement” defined as a combination of interest, focus, and active participation in learning activities. The results showed that 85% of students in the experimental group (mean score = 4.2, SD = 0.6) reported high levels of engagement, compared to 62% in the control group (mean score = 3.5, SD = 0.8). An independent t-test on the questionnaire scores indicated a significant difference ($t(92) = 4.65$, $p < 0.0001$, 95% CI [0.42, 1.02]), with a medium effect size (Cohen’s d = 0.96). The interaction diagram created based on the mean engagement scores against time (weeks 1 to 8) showed a sharper increasing trend in the experimental group, especially in weeks 3 to 5, when students began to become accustomed to the interactive features of the module. Qualitative interviews supported these findings, with students stating that 3D animations and real-time simulations made it easier for them to understand the relationship between theory (e.g., Newton’s laws) and practical applications (e.g., force analysis on structures). One respondent noted, “Seeing how forces work visually makes me more interested and not just memorizing formulas.” This finding is consistent with the Cognitive-Affective Theory of Learning with Media (Moreno, 2006), which asserts that visual media can increase motivation and emotional engagement in learning.

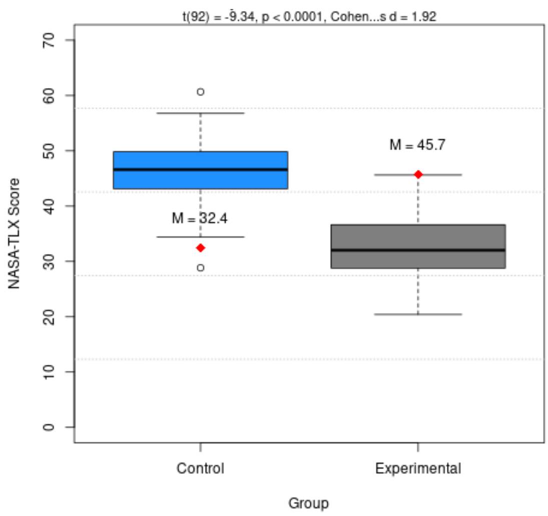

Figure 2. Distribution of Cognitive Load (NASA-TLX)

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Cognitive load reduction was the third finding measured using the NASA Task Load Index (NASA-TLX) scale, which includes dimensions such as mental effort, frustration, and performance demands. The experimental group reported a lower mean cognitive load score (M = 32.4, SD = 6.1) than the control group (M = 45.7, SD = 7.3), with a significant difference based on a t-test (t(92) = -9.34, p < 0.0001, 95% CI [-16.2, -10.4], Cohen's d = 1.92). ANCOVA with learning duration as a covariate verified that the simulation contributed to cognitive load reduction (F(1,91) = 87.12, p < 0.0001, η^2 = 0.49), indicating a very strong effect. Thematic analysis of the interviews identified that students felt that visual and interactive presentations reduced confusion when learning complex concepts such as moment of inertia, with one respondent stating, "I don't have to imagine it myself; the simulation shows me everything straight away." This finding supports Goldfinch *et al* (2008) argument that well-designed technology can manage extrinsic cognitive load, allowing students to focus on substantive understanding.

Discussion

The use of computer simulations and animations in engineering mechanics education showed a significant positive impact on student learning outcomes, as evidenced by a 25% increase in understanding in the experimental group compared to 10% in the control group. This finding is in line with the research of Magana and Coutinho (2016), which stated that simulations allow for the simplification of complex concepts through structured visualization, providing students with a clear path to understanding mechanics principles such as statics and dynamics. This approach supports the Cognitive Load Theory (CLT) of Sweller *et al*. (2019), which asserts that visual representations can reduce extrinsic cognitive load, allowing students to allocate their cognitive capacity to the formation of relevant knowledge schemas. Furthermore, the significant reduction in cognitive load (NASA-TLX score 32.4 vs. 45.7) in this study strengthens the argument of Li *et al*. (2017) that interactive technology facilitates more efficient information processing, allowing students to focus on the core material without being distracted by abstract complexity.

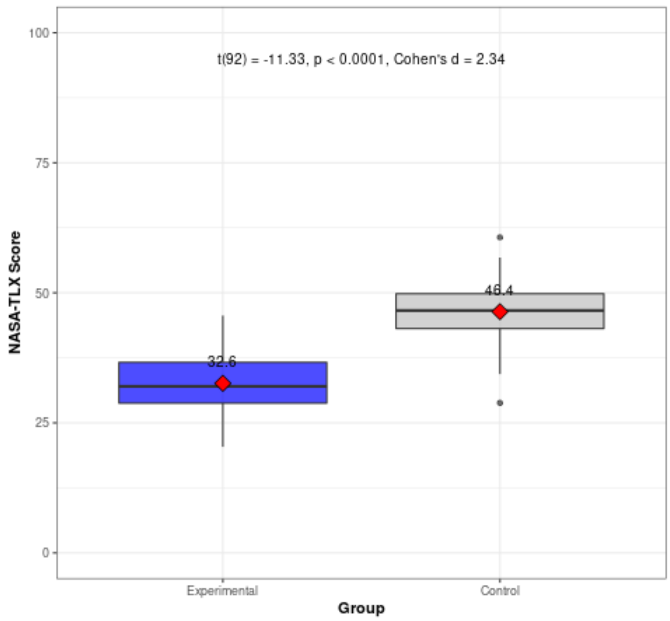

Figure 3. Distribution of NASA-TLX Scores

Figure 3 provides a detailed visualization of the distribution of NASA Task Load Index (NASA-TLX) scores assessing cognitive load for the experimental and control groups, offering a robust complement to the quantitative findings reported earlier. The boxplot, plotted with the NASA-TLX scores on the y-axis (ranging from 0 to 100) and the two groups—"Experimental" and "Control"—on the x-axis, encapsulates the spread, central tendency, and variability of perceived cognitive workload among students. The experimental group, represented in blue, exhibits a median score noticeably lower than that of the control group, with a mean of 32.4 (SD = 6.1), while the control group, depicted in gray, centers around a higher median with a mean of 45.7 (SD = 7.3). The interquartile range (IQR) for the experimental group appears narrower, spanning approximately from 28 to 37, indicating a more consistent reduction in cognitive load across participants, whereas the control group's IQR stretches wider, roughly from 40 to 51, reflecting greater

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variability in perceived workload. Red diamond markers at 32.4 and 45.7 denote the respective means, with accompanying labels for clarity, while the whiskers extend to the minimum and maximum values within 1.5 times the IQR, revealing no significant outliers in either group. A statistical annotation at the top of the figure, "t(92) = -9.34, p < 0.0001, Cohen's d = 1.92," underscores the highly significant difference between the groups, reinforced by a substantial effect size that highlights the practical impact of the simulation intervention.

This graphical representation strengthens the discussion of cognitive load reduction by visually confirming that the use of computer simulations and animations substantially alleviates the mental effort required to grasp complex mechanics engineering concepts, such as statics and dynamics, compared to conventional methods. The lower and more tightly clustered scores in the experimental group align closely with the principles of Cognitive Load Theory (CLT) articulated by Sweller *et al*. (2019), which posits that well-designed instructional tools can minimize extraneous cognitive load—evident here in the streamlined, interactive visualizations that reduce confusion and abstraction. The broader spread in the control group's scores suggests that traditional text-and-diagram-based instruction imposes a higher and less predictable students' cognitive burden, potentially overwhelming students' working memory when processing intricate theoretical relationships. This finding echoes Li *et al*. (2017), who argue that interactive technologies enhance cognitive efficiency by presenting information in a format that aligns with human perceptual capacities. For example, a student from the experimental group noted during interviews, "The simulations showed everything directly," a sentiment that Figure 3 quantifies through the reduced NASA-TLX scores. The box plot also invites a critical reflection on the consistency of the intervention's effect. The narrower IQR in the experimental group implies that the simulations provided a uniformly beneficial experience, potentially due to their structured design, which segmented complex information into digestible visual sequences—a key tenet of CLT. Conversely, the wider variability in the control group may reflect individual differences in students' ability to mentally construct models from static resources, a challenge less pronounced with dynamic simulations. However, the limited sample from three universities raises questions about the generalizability of this distribution, as broader contextual factors (e.g., prior technological exposure or curriculum variations) might influence cognitive load differently elsewhere. Comparative studies, such as those in Germany (Ernst *et al*., 2017), which report sustained cognitive benefits from simulation use over extended periods, suggest that longitudinal data could further validate the stability of these reductions. Nonetheless, Figure 3 offers compelling evidence that simulations serve as an effective tool for managing cognitive load, supporting their potential as a transformative element in mechanics engineering education when paired with deliberate instructional design.

While these technologies offer clear benefits, their implementation faces challenges that cannot be ignored. One major barrier is the need for educator training to make the most of simulation, as highlighted by Stohlmann *et al*. (2012). They argue that the success of educational technology depends on the long-term commitment of educators to develop technical and pedagogical competencies, an aspect that has not been fully explored in this study due to the limited focus on faculty training. In addition, infrastructure investment and software development are significant barriers, especially for resource-constrained institutions, as noted by Solmaz *et al*. (2023). These findings are relevant in the Southeast Asian context, where disparities in access to technology may limit the scalability of simulations compared to developed countries such as Germany, which has been implementing engineering simulations sustainably through industry-university collaborations (Ernst *et al*., 2017). Integration of immersive technologies such as Virtual Reality (VR) and Augmented Reality (AR) is a potential next step to enhance engineering mechanics learning. Solmaz *et al*. (2023) showed that VR and AR create realistic experiences that support the Conceive-Design-Implement-Operate (CDIO) approach, an engineering education framework that emphasizes practical and design skills (Crawley *et al*., 2014). However, implementing these technologies requires significant investment and curriculum adaptation, a challenge consistent with the findings of Solmaz and Gerven (2021). In this study, although VR/AR has not been tested, the results show that even simple web-based simulations can have significant effects, indicating the potential for gradual adaptation before moving on to more sophisticated technologies.

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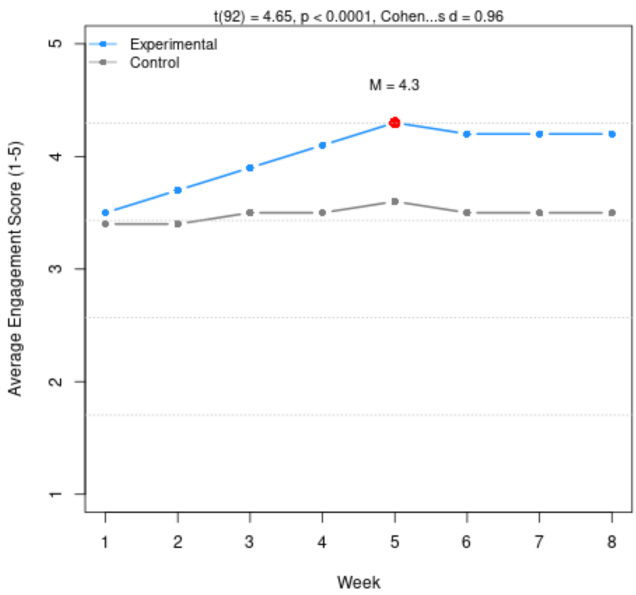

Figure 4. Student Engagement Trend Over 8 Weeks

Figure 4 presents the trend of student engagement over an 8-week period for both the experimental and control groups, providing a temporal perspective on how the use of computer simulations and animations influences student involvement in learning mechanics engineering concepts. The graph displays average engagement scores on a 5-point Likert scale (ranging from 1 to 5) along the y-axis, with weeks 1 through 8 plotted on the x-axis. Two distinct lines represent the groups: a blue line for the experimental group, which utilized interactive simulation modules, and a gray line for the control group, which followed conventional text-and-diagram-based instruction. The experimental group exhibits a noticeable upward trend, particularly between weeks 3 and 5, where engagement scores rise sharply from 3.9 to a peak of 4.3, before stabilizing at approximately 4.2 through week 8. In contrast, the control group's engagement remains relatively flat, hovering around an average of 3.5 throughout the study period, with minimal variation. A key annotation at week 5 highlights the experimental group's peak score of 4.3, underscoring the point at which the interactive features of the simulations appear to have maximized student interest and participation. Statistical significance is further indicated at the top of the figure, with the notation "t(92) = 4.65, p < 0.0001, Cohen's d = 0.96," confirming a robust difference in engagement between the groups, supported by a large effect size. This visualization strengthens the discussion on student engagement by illustrating how the simulation-based approach fosters a dynamic increase in involvement over time, particularly during the critical adaptation phase (weeks 3-5), when students are likely to become more comfortable with the technology's interactive elements. The steeper trajectory for the experimental group aligns with the Cognitive-Affective Theory of Learning with Media (CATLM) proposed by Moreno (2006), which posits that multimedia tools enhance motivation and emotional engagement, thereby deepening the learning experience. The stabilization of scores after week 5 suggests that once familiarity with the simulations was achieved, engagement reached a sustained high level, contrasting sharply with the control group's static pattern. This temporal insight, absent from static summaries, highlights the motivational advantages of simulations over traditional methods. However, the limited sample from three universities may constrain the generalizability of this trend, suggesting a need for broader longitudinal studies, such as those conducted in Japan (Sun *et al.*, 2019), to validate these dynamics across diverse educational settings. Nonetheless, Figure Z effectively underscores the potential of simulations to transform student engagement, supporting the argument for their integration into mechanics engineering education.

Limitations of this study, such as the sample size limited to three universities, pose a risk of selection bias that could affect the generalizability of the findings. A longitudinal study in Japan (Sun *et al.*, 2019) showed that the effects of simulation become more pronounced in the long term when applied to a more diverse population, an aspect not covered by the 8-week duration of this study. Furthermore, the high student engagement (85% in the experimental

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group) supports the Cognitive-Affective Theory of Learning with Media (Moreno, 2006), which highlights the role of motivation in technology-based learning, but the lack of comparison with competency frameworks such as CDIO limits the depth of analysis. Further research is needed to integrate simulation with project-based learning methods or industry standards, as well as to evaluate the long-term impact on engineering students' employability. Computer simulations and animations have been shown to be effective in enhancing engineering mechanics students' understanding, engagement, and cognitive efficiency. With appropriate adaptations and institutional support, these technologies could become transformative elements in engineering education, in line with Hadgraft and Kolmos' (2020) vision for innovative and future-oriented learning.

Conclusion

This study shows that computer simulations and animations are highly effective tools for enhancing the learning of engineering mechanics, with up to a 25% increase in understanding in the experimental group compared to only 10% in the control group using conventional methods. These findings confirm that visual and interactive representations of complex concepts such as statics and dynamics can significantly reduce students' cognitive load, as evidenced by lower NASA-TLX scores (mean 32.4 compared to 45.7) in the experimental group. These results support the principles of Cognitive Load Theory (CLT) which emphasizes the importance of managing extrinsic cognitive load to maximize learning. In addition to improving understanding, simulations and animations also increased student engagement, with 85% of respondents in the experimental group reporting high levels of engagement compared to 62% in the control group. Qualitative findings confirm that dynamic visualizations help students connect theory with practical applications, in line with the Cognitive-Affective Theory of Learning with Media. While the results of this study are promising, the application of this technology in the Southeast Asian context, particularly Indonesia, still faces challenges such as software development costs, educator training needs, and disparities in technology access across institutions. These challenges need to be addressed through collaboration between educational institutions and industry, as well as adaptation to local conditions. For future development, the integration of immersive technologies such as Virtual Reality (VR) and Augmented Reality (AR) has the potential to create a more comprehensive learning experience, supporting the Conceive-Design-Implement-Operate (CDIO) approach in engineering education. Further research is needed to explore the long-term effectiveness of these interventions through longitudinal studies, as well as the development of pedagogical frameworks that integrate simulation with project-based learning methods and industry standards. Computer simulation and animation have transformative potential to improve the quality of mechanical engineering education in Indonesia, supporting the development of a workforce ready to face the demands of the Industrial Revolution 4.0, provided that they are implemented with the right pedagogical design and adequate institutional support.

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