A Glimpse into the Future of Civil Engineering Education: The New Era of Artificial Intelligence, Machine Learning, and Large Language Models

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Introduction

In recent years, the integration of machine learning (ML) and artificial intelligence (AI) into education has revolutionized the field, creating opportunities for enhancing teaching and learning (Guan et al. 2020). This transformation is significant in the domain of civil engineering (Naser 2022), where students must grasp complex theoretical concepts and acquire extensive practical knowledge to succeed in their careers. This demand necessitates innovative approaches that can provide personalized, efficient, and effective learning experiences. AI, with its ability to process vast amounts of data and learn from patterns, is uniquely positioned to meet these demands. Large language models (LLMs), such as ChatGPT, have shown potential in providing personalized learning experiences, offering real-time assistance, and automating tasks (Plevris et al. 2023). These capabilities can address some persistent challenges in civil engineering education, such as the need for individualized attention, timely feedback, and catering to different learning needs (Filippi and Motyl 2024). In this paper we explore the application of AI, ML, and LLMs, in civil engineering education and highlight five key areas where AI can make a significant impact. We show that the integration of AI technologies in civil engineering education offers benefits, including improved learning outcomes (LOs), efficiency in teaching, and enhanced engagement. However, it also presents challenges. Through a comprehensive exploration of these topics, we aim to provide valuable insights into how AI techniques can be leveraged to enhance the education of civil engineers, contributing to the ongoing dialogue about the future of civil engineering education in the age of AI.

Background

The education of civil engineers covers a comprehensive array of topics, including material science, mechanics, structural analysis, and design principles. These subjects form the foundation of the field, enabling engineers to ensure the safety, functionality, and sustainability of our structures. Historically, civil engineering education has relied on traditional pedagogical approaches based on textbooks, lectures, hands-on projects, and laboratory work. Whereas these methods are effective, they have limitations. The one-size-fits-all approach often fails to address the diverse learning needs of students. Large classes can limit the amount of personalized attention each student receives, and the static nature of textbooks and lectures may not fully engage students. The advent of AI presents a transformative opportunity to supplement and enhance traditional educational methods, offering several advantages. Javaid et al. (2023) identified and discussed the significant features and applications of ChatGPT in the education system. Ouyang and Jiao (2021) outlined the evolution of AI in education through three paradigmatic shifts: AI-directed learning; AI-supported learning; and AI-empowered learning. Babović et al. (2023) used a synergizing approach with four different computing paradigms and four different management domains for teaching computing for complex problems in civil engineering using ML. Several educational institutions and online platforms have begun integrating AI technologies into their programs. Case studies from early adopters provide valuable insights into the benefits and challenges of using AI in education. For example, some institutions have implemented AI-driven adaptive learning systems (Kabudi et al. 2021) that tailor coursework to individual student needs, whereas others have developed AI-powered virtual labs (Potkonjak et al. 2016). Yet, the potential of AI in civil engineering education extends far beyond these initial applications (Kamalov et al. 2023). Future advancements could include more sophisticated AI systems capable of providing personalized and adaptive learning experiences, and AI-driven tools that facilitate collaboration and communication. As AI evolves, its role in civil engineering education is likely to become increasingly important, paving the way for more innovative and effective teaching and learning.

Potential Applications of AI, ML, and LLMs in Civil Engineering Education

1. **Virtual Tutors and Intelligent Learning Systems**. AI has the potential to create personalized learning pathways that are specifically tailored to meet the unique needs of individual students. This is important in civil engineering education, where students must grasp complex concepts and develop practical skills at their own pace. ML algorithms can analyze vast amounts of data such as test scores, assignment grades, or interaction logs. By identifying trends and patterns, they can generate detailed profiles for each student, highlighting their strengths and weaknesses. Based on these insights, AI systems can dynamically adjust the difficulty and content of coursework in real-time through: (1) **Adaptive Testing**: tailoring the difficulty of questions, providing simpler ones for students who are struggling and challenging ones for those performing well (Sampayo-Vargas et al. 2013); (2) **Customized Assignments**: creating assignments that focus on areas where a student needs practice (Ingkavara et al. 2022); and (3) **Personalized Study Plans**: generating study plans that align with the student's schedule, learning preferences, and academic goals (Wu et al. 2024).

AI-powered educational tools offer a highly interactive and engaging learning experience, which is particularly beneficial in civil engineering education. AI-based virtual tutors offer a revolutionary way to support students by answering questions, explaining complex concepts in simple terms, and guiding through basic or advanced topics (Bassner et al. 2024). By providing instant feedback, these tools help students overcome obstacles quickly and effectively, improving comprehension and retention. AI systems can offer detailed explanations and step-by-step solutions to complex problems, helping students understand not just the *how* but also the *why* behind engineering principles. Additionally, AI can suggest supplemental resources tailored to the student's individual progress and areas of improvement, offering personalized learning pathways. This 24/7 availability of AI-powered tutors ensures that students receive continuous support, enhancing their learning experience. Rather than catering to predefined learning styles, AI can adapt its instructional methods based on real-time data about student performance (Gligorea et al. 2023). For example, it can present information visually through diagrams and infographics, use audio explanations where needed, or offer interactive simulations that involve active participation. By dynamically adjusting its approach based on how well a student is grasping the material, AI can ensure that the learning experience is truly personalized and effective for each and every individual.

2. **Automated Grading and Feedback**. Traditional grading methods can be time-consuming and prone to error. AI has the potential to revolutionize the grading process in civil engineering education, making it more efficient and consistent (Messer et al. 2024). By leveraging AI, the evaluation process can be streamlined. AI can excel in grading **objective questions**, such as multiple-choice, true/false, and fill-in-the-blank formats. This automation significantly reduces the time instructors spend on grading, allowing them to focus on more complex aspects of teaching. For **subjective questions**, such as essays, design assignments, and problem-solving tasks, AI can provide preliminary evaluations. Advanced natural language processing (NLP) algorithms can analyze student responses and assess the coherence and correctness of the content. Whereas AI may not yet fully replace human judgment for subjective assessments, it can offer valuable initial evaluations. Instructors can review the AI-generated assessments, refining and finalizing the grades. Similar AI-supported approaches have proven successful in fields like medicine, where radiologists rely on AI systems for tasks such as prioritizing urgent examinations, automating measurements, and aiding in lesion identification (Boeken et al. 2023; Ibba et al. 2023).

   Unlike traditional grading systems, where feedback may come days or weeks after submission, AI can analyze and respond to student work in **real-time**, which is particularly useful in large classrooms (Lee 2023). This immediate feedback loop offers several benefits: (1) **Understanding Mistakes**: By addressing errors immediately, students can correct misunderstandings before they become ingrained, leading to deeper comprehension; (2) **Improving LOs**: Real-time feedback allows students to adjust their learning strategies on the fly. For instance, if a student consistently struggles with a particular concept, AI can provide additional targeted resources; and (3) **Encouraging Continuous Improvement**: Regular, timely feedback fosters a culture of continuous improvement. Students are likely to engage and remain motivated when they see that their efforts are being monitored.

3. **Interactive Simulations and Virtual Labs**. AI-driven interactive simulations can transform the way students gain practical experience. Traditional physical models are costly, time-consuming, and limited in scope. AI-powered simulations overcome these limitations by providing dynamic, virtual environments where students can engage in complex tasks (Al-Ansi et al. 2023). Such AI-driven simulations allow students to gain **hands-on experience** in a virtual setting (Lestari 2023). They can interact with detailed models, manipulate variables, and observe the effects in real-time, helping bridge the gap between theoretical knowledge and practical application. One of the most significant advantages of such simulations is their ability to **model complex and hazardous scenarios** safely and accurately (Lagaros and Plevris 2022). For instance, students can study the impact of earthquakes on structures, observing how different materials and construction techniques perform under seismic loading. Similarly, simulations can model the effects of wind on structures, allowing students to understand aerodynamic forces and how they affect the structural response. By providing interactive, realistic, and safe environments for hands-on learning, these technologies enhance students' understanding of complex concepts and prepare them for real-world challenges. As AI continues to evolve, the capabilities of virtual labs and simulations will expand, offering even more sophisticated and immersive educational experiences (Dai and Ke 2022).

4. **Enhancing Collaboration and Communication**. Group projects are an integral part of civil engineering education, fostering teamwork, problem-solving skills, and the ability to work collaboratively on complex tasks. AI tools can significantly enhance the collaborative process by streamlining communication, organizing tasks, and tracking progress. AI-powered platforms can help organize and assign tasks within a group. LLMs can assist in breaking down projects into manageable tasks, assigning tasks to different members and setting proper deadlines. AI can monitor the progress of group projects in real-time, track task completion, identify bottlenecks, and provide reminders for upcoming deadlines. AI tools can facilitate seamless communication among team members, regardless of their physical location (Al Shloul et al. 2024). A LLM can serve as a virtual assistant, helping coordinate meetings, summarizing minutes, and ensuring that important messages are communicated clearly and promptly. It can also play a role in conflict resolution by providing unbiased suggestions and facilitating discussions to address any disagreements or issues that arise within the team, maintaining a positive environment (Aref 2024). AI can enhance discussion forums, a valuable component of the learning process. It can moderate discussions to maintain a respectful and constructive environment, filter out inappropriate content, ensure compliance with forum guidelines, and promote positivity. It can respond to FAQs, providing instant answers to common queries, reducing the repetitive workload for instructors and ensuring that students receive timely responses. It can guide discussions by suggesting relevant topics, posing thought-provoking questions, and encouraging deeper analysis of the subject matter. By facilitating group projects, moderating discussion forums, and integrating with advanced collaboration tools, AI ensures that students can work together effectively, share knowledge, and develop their skills. As AI technologies continue to advance, their role in fostering collaborative and communicative learning environments will only grow, leading to more innovative and productive educational experiences.

5. **Resource Management and Curriculum Development**. AI can play a crucial role in **optimizing resource management** by recommending personalized content tailored to the individual learning needs and interests of students. This capability ensures that each student has access to the most relevant and

beneficial resources. AI systems can analyze a student's performance, learning style, and interests to recommend a variety of educational materials, including articles, textbooks, and online courses. By providing resources that match the student's level of understanding and areas of interest, AI helps students engage deeply with the material, promoting a more effective learning process (Bhutoria 2022). AI can integrate with adaptive learning platforms that continuously assess a student's progress and adjust recommendations accordingly. If a student struggles with a specific topic, the platform can suggest additional readings and exercises or recommend a diverse range of multimedia content, instructional videos, interactive simulations, and webinars, catering to different learning preferences.

AI offers powerful tools for **curriculum design**, enabling educators to create more effective and up-to-date educational programs that align with industry standards and technological advancements (Padovano and Cardamone 2024). By leveraging AI, educators can ensure that their curriculum remains relevant, comprehensive, and responsive to the evolving needs of the field of civil engineering. AI can analyze the effectiveness of existing curricula by examining student performance data, feedback, and outcomes. This analysis can identify strengths and weaknesses in the current curriculum, highlighting areas where students consistently perform well and areas where they struggle. Based on these insights, it can suggest specific adjustments to improve educational outcomes. AI can help ensure that the curriculum aligns with current industry standards and technological advancements. By analyzing trends in the civil engineering field, such as emerging materials, new construction techniques, and updated regulations, it can suggest updates that reflect these changes. AI can assist in developing personalized curricula that cater to diverse student needs. For example, advanced students may benefit from more challenging coursework and research opportunities, whereas those needing extra support can receive additional foundational materials and tutoring. In addition, AI can use predictive analytics to forecast future trends in the field of civil engineering and suggest proactive adjustments. This forward-looking approach helps educators stay ahead of industry changes and prepare students for future challenges and opportunities. By recommending personalized learning resources and assisting in the design of effective, up-to-date curricula, AI helps ensure that students receive a high-quality education that prepares them for the challenges and opportunities of the profession. As AI technologies continue to evolve, their role in resource management and curriculum development will become increasingly important, leading to more innovative and effective educational strategies.

Challenges and Considerations

Whereas the integration of AI into civil engineering education offers transformative potential, it also presents several challenges that need to be carefully addressed to ensure both effective implementation and ethical practice (Ali et al. 2024). These challenges span technical, ethical, pedagogical, and societal aspects, all of which require careful consideration and ongoing evaluation.

Technical Integration and Infrastructure: One of the primary technical challenges is the integration of AI tools with existing learning management systems. This integration requires not only seamless interoperability but also significant technical expertise and resources to maintain and optimize. Institutions may need to upgrade their IT infrastructure, improve network capacity, and provide training for technical staff to ensure the continuous and smooth operation of AI-powered platforms (Qazi et al. 2024). Furthermore, compatibility issues between proprietary AI tools and existing educational platforms can create friction, leading to disruptions in the learning experience if not properly managed.

Data Privacy and Security: Protecting the privacy and security of student data is paramount when incorporating AI systems into educational environments. AI tools often require access to sensitive data, including academic records, personal information, and real-time performance metrics. Ensuring the implementation of robust data encryption, secure storage, and strict access controls is essential to prevent unauthorized access and data breaches (Sanfilippo et al. 2023). Educational institutions must comply with data protection regulations such as the European Union's General Data Protection Regulation (GDPR) (Jekabsone 2023) or the US Family Educational Rights and Privacy Act (FERPA). Institutions should also establish clear data policies that define how student data will be collected, used, and protected, thereby fostering transparency and trust (Romanou 2018).

Ethical Concerns and Bias in AI: AI algorithms are only as good as the data they are trained on. One significant concern is the potential for bias in AI systems, which can perpetuate inequities if the data used are not sufficiently diverse or representative (Mehrabi et al. 2021). Bias can affect AI-driven assessments, recommendations, and even feedback, leading to unfair treatment of students from underrepresented groups. Ensuring fairness requires the use of diverse datasets and the implementation of fairness-aware algorithms (Holmes et al. 2022). Regular audits and evaluations of AI systems must be conducted to detect and mitigate biases, ensuring that AI serves all students equitably. Moreover, educators and institutions should have clear insights into the decision-making processes of AI systems. This level of transparency helps build trust and allows for human oversight, ensuring that AI outputs are used appropriately and in context (Binns 2020).

Balancing AI and Human Instruction: AI should not be seen as a replacement for human instructors, but rather as a tool that complements and enhances their teaching efforts. Human interaction is essential for fostering critical thinking, creativity, and emotional intelligence—areas where AI still falls short (Selwyn 2019). Educators must be equipped with the skills to integrate AI effectively into their teaching practices, utilizing AI's strengths in data processing and adaptability while maintaining their own role in guiding, mentoring, and inspiring students. Continuous professional development and training are necessary to ensure that educators can use AI systems effectively and judiciously.

Accessibility and Inclusivity: Ensuring that AI-driven platforms are accessible to all students, including those with disabilities, is crucial for creating an inclusive learning environment. AI tools should comply with accessibility standards such as the Web Content Accessibility Guidelines (WCAG), offering features like screen readers, text-to-speech functionality, and alternative input methods to accommodate a diverse range of learners (Burgstahler 2020). Furthermore, AI systems must be designed with inclusivity in mind, ensuring that they cater to students with varying learning needs and preferences. Institutions should monitor the accessibility of AI systems and make necessary adjustments to improve user experience across different demographics.

Ethical Transparency and Accountability: It is critical to ensure transparency in the workings of AI systems, particularly in how decisions are made regarding student evaluations, feedback, and learning paths. The decision-making processes of AI tools should be interpretable and well-documented, enabling educators and students to understand how AI-generated recommendations and assessments are made. This transparency fosters accountability, ensuring that AI outputs are not accepted blindly but are critically

examined by educators and adjusted when necessary (Chaudhry et al. 2022).

Cost and Resource Allocation: Finally, integrating AI into civil engineering education is not without financial implications. The cost of acquiring, maintaining, and updating AI tools, along with training staff and faculty to use them effectively, can be substantial. Institutions must carefully evaluate the long-term benefits against these costs to ensure that AI integration is sustainable. Additionally, disparities in access to advanced technologies between well-funded and underfunded institutions can exacerbate inequalities in educational opportunities (Bulathwela et al. 2024).

Conclusions

In conclusion, the integration of AI, ML, and LLMs, into civil engineering education presents exciting opportunities and has the potential to significantly enhance the learning experience. By providing personalized learning, automated assistance, and enhanced collaboration, these tools can effectively help prepare the next generation of civil engineers. However, to fully realize these benefits, it is essential to address the associated technical, pedagogical, and ethical challenges with thoughtful planning, robust policies, and continuous evaluation. This will ensure that AI tools are used effectively and responsibly, ultimately benefiting students, educators, and the broader community. Embracing these innovations responsibly will pave the way for a more efficient, inclusive, and effective educational landscape in civil engineering education.

Data Availability Statement

No data, models, or code were generated or used during the study.

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