Engineering Education Review

RESEARCH

An integrated competency model for engineering teachers: A comparative framework insights

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ABSTRACT

The accelerating demands of engineering education in the 21st century, coupled with the emergence of artificial intelligence (AI), require a redefinition of the competencies of engineering educators. This study develops an integrated competency model tailored to the needs of modern engineering education. It synthesizes five established frameworks and incorporates recent research achievements on engineering teacher competencies. Through a detailed comparative analysis, this study refines a model that balances technical competence, pedagogical competence, and professional and ethical competence. The model is visually represented to highlight the interconnections between these domains. This study provides a foundation for improving faculty development and aligning teaching with industry and societal demands. It offers both theoretical insight and practical guidance for building educational excellence in engineering for a sustainable future.

Key words: engineering education, competency frameworks, artificial intelligence, pedagogical knowledge, engineering pedagogy

INTRODUCTION

The engineering education landscape is undergoing profound transformation. Global challenges—sustainability, digitalization, and ethical governance—combined with the pervasive integration of artificial intelligence (AI), demand that engineering graduates acquire not only technical proficiency but also the ability to act ethically and innovatively within society. Engineering educators thus face heightened expectations: they must integrate advanced technical knowledge with dynamic teaching strategies and model professional and ethical standards. Traditional teaching approaches and skillsets are no longer sufficient; instead, a dynamic and multifaceted competency model is essential to address these evolving requirements (EbrahimNejad, H., 2017).

Recent research highlights the urgent need to update traditional competency models to reflect emerging educational technologies and evolving engineering practices. In this context, it is important to clarify two related concepts used in this study: competency and competence. Competency refers to behavior-based characteristics such as attitudes, values, and motivations that underlie effective performance. Competence, by contrast, relates to observable skills, qualifications, and knowledge-based capacities. Together, they form a holistic profile of an effective educator, capable of fostering both technical and moral excellence in engineers.

This study seeks to develop a comprehensive competency model for engineering educators, synthesizing insights from five established frameworks while integrating the critical role of AI. By bridging traditional competencies with modern demands, the proposed model equips educators to train engineers who

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are prepared to thrive in a rapidly evolving, technologically complex world.

LITERATURE REVIEW

Competency models serve as structured frameworks that define the knowledge, skills, and abilities (KSAs) essential for achieving professional excellence. Initially conceptualized by McClelland and Boyatzis, these models emphasize both observable behaviors and underlying traits that drive effective performance (McClelland, 1973; Boyatzis, 1982). Over the years, competency models have found extensive application across educational and industrial domains, providing a foundation for evaluating and developing professional capacities.

Recent studies highlight the integration of AI in competency models for engineering educators, such as adaptive learning platforms and AI-based analytics for educational improvements (Akinwalere & Ivanov, 2022; Strielkowski *et al.*, 2025). Additionally, interdisciplinary approaches combining sustainability with ethical engineering practices are gaining traction, as emphasized in recent works (European Commission, 2025; Liu *et al.*, 2022).

In the context of education, competency frameworks have evolved to address the diverse and dynamic roles of educators. These models highlight the interplay between technical expertise, pedagogical strategies, and professional ethics—critical elements for preparing educators to meet the challenges of modern teaching environments (Liu *et al.*, 2022). Among these frameworks, the Engineering Body of Knowledge (EBOK) and the Department of Education and Training of Western Australia's (2004) competency model are particularly notable. These models cater specifically to the dual demands of technical proficiency and effective pedagogy required of engineering educators. They underscore key competencies such as specialized knowledge of engineering principles, curriculum design, and ethical responsibility (Wankat & Oreovicz, 2015).

Engineering educators are uniquely positioned at the intersection of technical innovation and educational practice. They must possess advanced technical expertise while mastering instructional methods to effectively convey complex concepts to students. For instance, the EBOK outlines competencies in areas such as problem-solving, professional communication, and teamwork, whereas the Western Australian framework emphasizes classroom management, teaching methodologies, and professional knowledge. Together, these models provide a comprehensive view of the core attributes required for engineering educators (Wankat & Oreovicz, 2015).

The growing integration of AI into engineering education further redefines the competencies required of educators. AI's potential to transform teaching and learning processes introduces new opportunities and challenges. AI tools, such as adaptive learning platforms, virtual laboratories, and automated grading systems, enhance the educational experience by enabling personalized learning pathways and reducing administrative burdens. These advancements demand that educators acquire a robust understanding of AI applications and their implications within the engineering domain (Shah, 2023).

Moreover, AI tools are instrumental in fostering innovation and creativity in engineering education. For example, virtual labs powered by AI allow students to engage in simulations of real-world engineering problems, providing hands-on experience without the constraints of physical resources. Similarly, AI-driven analytics enable educators to monitor student performance in real time, identify learning gaps, and implement targeted interventions. To leverage these tools effectively, educators must not only master AI technologies but also integrate them seamlessly into their teaching strategies (Akash & Suganya, 2024).

Competency modeling for engineering educators has advanced significantly in recent years. Modern frameworks increasingly emphasize AI literacy, sustainability ethics, and interdisciplinary collaboration. Recent empirical studies show that effective engineering education requires a fusion of technical competence, advanced pedagogy, and ethical reasoning. AI integration further complicates this task, as educators must now master new teaching tools while cultivating critical thinking about AI's societal impact. Nevertheless, much of the existing literature lacks synthesized models that explicitly interconnect these three domains. This study aims to fill that gap through an integrated, empirically informed framework.

METHODOLOGY

Framework selection

The comparative analysis followed a systematic approach to evaluate the five models. Criteria included relevance to technical, pedagogical, and ethical competencies, adaptability to AI integration, and applicability to diverse educational contexts. Each framework was scored based on these criteria, with overlapping competencies synthesized into the new model.

The methodology of this study involves a systematic review and synthesis of existing competency models. These models were chosen based on their relevance to the contemporary needs of engineering education and their applicability to the role of engineering educators. The five models reviewed in this paper are as follows.

McClelland's Iceberg Model (McClelland, 1973).
Focuses on the differentiation between observable behaviors and underlying traits, suggesting that competencies are largely driven by internal, unobservable factors. It is evident that McClelland's outlined competencies are visualised as observable and unobservable behaviours. Those observable are small part of the layers such as knowledge and skills. Whereas, unobservable ones are under the water level. Therefore, social roles, self image, traits and motives are deeper in an individuals competence. The basis of this model deduces the holistic view of competency development. These competences are connected to each other with variant levels of exposure. It can be further analysed that the appearance of the upper layers are smaller and shallower, however the lower layer is deeper and layer. This signifies the greater influence of hidden competences that drive individuals to be excellent. Thus, in assessing the connection from motives to knowledge, evidently growth of competence has more power in the inner self.

A limitation of this model is the challenge of explicit assessing invisible competencies that are hard to reliably measure. The unobservable nature displays a greater effort to uncover real behaviours and competencies. This demands a need for assessments that develop individuals inner self. Hence, from this analysis competencies such as: creativity, revolution, self reflection/evaluation, self awareness, innovation, AI/digital literacy could be evaluated to add to the framework (Mertens, 2004).

Boyatzis' Onion Model (Boyatzis, 1982)
Represents competencies as layered attributes, including self-awareness, interpersonal skills, and cognitive abilities, all of which contribute to an individual's professional performance. The Onin model depicts competencies as layers of an onion. As seen in the model below, the Onion presented by Richard Boyatzis compiles layers from the centre outwards of prominence. Hence, the most prominent in the centre of personal characteristics and motivation pushes the idea that the core is the first hierarchy level that bounds competent success. Boyatzis' competencies outside of the core include values, social role, attitude, motivation, self image, knowledge and skills. In turn, it reflects that the central competencies are essential for development and are innate to individual function. This model provides a display for development of training, as the efforts most dominantly fall in the personality of an individual. In identifying these competencies it is evident there are gaps in the development. As competency is dynamic in the new era, there are areas that fall short of the necessary level of interconnectedness that are driving industries forward.

American Association of Engineering Societies (AAES) Engineering Competency Model
This model was orchestrated by the AAES. It explains the array of competences that entry level engineers must obtain for the position. This pyramid shaped model is comprehensive in the fact that engineering competencies are outlined explicitly. It also displays the assessment in order of engineering training industry standards. This is beneficial to engineering students who should incorporate the standards required to be an engineer. However, this competency model is broad to the whole engineering field, and fails to delve into specific fields. Hence, it is recommended that a new feature to improve this model is an interdisciplinary collaboration to clearly display the knowledge in a variety of areas to connect.

Western Australian Competency Model (Department of Education and Training of Western Australia, 2004)
Focuses on essential competencies for educators, with a specific emphasis on teaching skills, classroom management, and knowledge dissemination. This model is specifically tailored to the Australian standards of engineering competencies. The dimensions of the framework are explicit and easy to follow for professional attributes in the centre, followed by professional knowledge, with professional practice on the outside. It infers there are stages to development in engineering that require following a chain of training blocks to achieve all competencies in the engineering field. This model is prominent for the region specific set of training engineers, therefore accordingly is not easily adaptable to other regional areas of engineering development programs. One recommendation could be the addition of new era technology skills to integrate the use of AI into training classes. This could aide the future of the industry with the potential bounding nature of digital technology to individual excellence.

The engineering body of knowledge
A framework by the National Society of Professional Engineers (NSPE) that outlines the technical and professional competencies needed for engineers, including ethics, professional communication, and teamwork (National Society of Professional Engineers, 2013). This competency model contains the greatest number of competencies in order for engineers to be excellent in the development program. Designed by the NSPE, this model is refined to detail ethical considerations into education. On the one hand, this drives engineers to combine a high standard of professional responsibilities

in a clear structure for the necessary ethical obligations to be understood. The qualifications set out by the committee provide a knowledge bank as referenced below.

On the other hand, a limitation is the need for incorporating responsibility in sustainability in combination with the ethical responsibility listed. This may enhance the interpersonal nature of the competence for inner excellence. Increasing this importance in the field of engineering stems the future of the dynamic environment (The Royal Academy of Engineering, 2007).

To enhance the quantitative understanding of the competency frameworks, we conducted a comparative analysis using metrics such as competency coverage, emphasis on AI integration, and alignment with 21st-century engineering education needs (Garrison, 2003).

Comparative analysis process

To address the evolving demands of engineering education in the 21st century, a comprehensive comparative analysis was conducted to identify the overlapping and complementary elements within five established competency frameworks. The aim of this analysis was to synthesize these elements into a unified and robust competency model tailored specifically for engineering educators. This model integrates traditional competencies with the transformative role of AI, reflecting the dynamic changes shaping modern engineering education.

The frameworks analyzed include McClelland's Iceberg Model, Boyatzis' Onion Model, the AAES Engineering Competency Model, the Western Australian Competency Model, and the EBOK. Each of these frameworks offers unique insights into technical expertise, pedagogical strategies, and professional ethics. By synthesizing their strengths, the study derived a conceptual model that aligns with the interdisciplinary and technological nature of contemporary engineering practice.

The resulting model emphasizes three primary domains: technical expertise, pedagogical knowledge, and AI-related skills (Fadel & Trilling, 2009). Traditional competencies, such as problem-solving and ethical responsibility, are enhanced by the integration of AI-driven tools and methodologies, which support personalized learning, advanced analytics, and automation. This synthesis underscores the multi-dimensional role of engineering educators as both facilitators of knowledge and leaders in technological innovation. The proposed framework sets a foundation for equipping educators to train future engineers capable of thriving in a rapidly advancing global landscape.

PROPOSED INTEGRATED COMPETENCY MODEL

The proposed integrated competency model combines aspects of five established frameworks, adapting them to meet the unique needs of engineering educators in the AI age. It identifies three primary domains, each comprising distinct yet interconnected competencies (Figure 1).

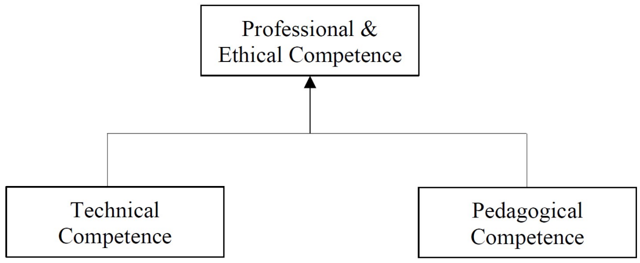

Figure 1. Three primay domains of proposed model

Technical competency

Engineering educators must possess advanced technical knowledge and demonstrate the ability to adapt to emerging technologies. This includes a comprehensive understanding of core engineering principles, cutting-edge innovations such as AI, and the capacity to stay abreast of industry trends. Mastery of AI tools, including automated grading systems, virtual laboratories, and personalized learning platforms, is particularly critical. These technologies not only streamline the educational process but also enable educators to prepare students for real-world challenges in technologically advanced environments.

Pedagogical competency

Effective teaching extends beyond subject matter expertise; it demands proficiency in instructional design, student engagement, and assessment strategies. Pedagogical competency encompasses the integration of AI-driven methodologies into teaching practices. Examples include leveraging AI-powered teaching assistants, adaptive learning platforms, and virtual labs to enhance the educational experience. These tools allow for personalized instruction tailored to individual learning styles, thus improving student outcomes. Additionally, fostering collaboration with industry stakeholders ensures that curricula remain relevant to the demands of modern engineering practices.

Professional and ethical competency

Engineering educators play a crucial role in modeling professional behavior and instilling ethical responsibility in their students. This domain emphasizes ongoing professional development, the promotion of ethical decision-making, and an awareness of engineering's societal impacts. As AI becomes a cornerstone of engineering practice, educators must address ethical concerns surrounding its application, such as bias in algorithms and data privacy issues. By integrating these discussions into their teaching, educators can prepare students to navigate the complex ethical landscape of the AI-driven engineering field.

Implications of the proposed model

This study's proposed competency framework aligns with the qualifications needed for engineering educators to thrive in the AI era. The framework represents three interdependent domains. Technical Competency: Incorporates specialized knowledge and technological adaptability. Pedagogical Competency: Encompasses advanced teaching methodologies and industry collaboration. Professional and Ethical Competency: Includes social capability, teacher morality, and ethical considerations related to AI. The integration of AI as both a tool and a transformative force highlights its role in reshaping traditional competencies. By fostering interconnectedness between these domains, the framework ensures educators are equipped to address the multifaceted challenges of modern engineering education (Figure 2).

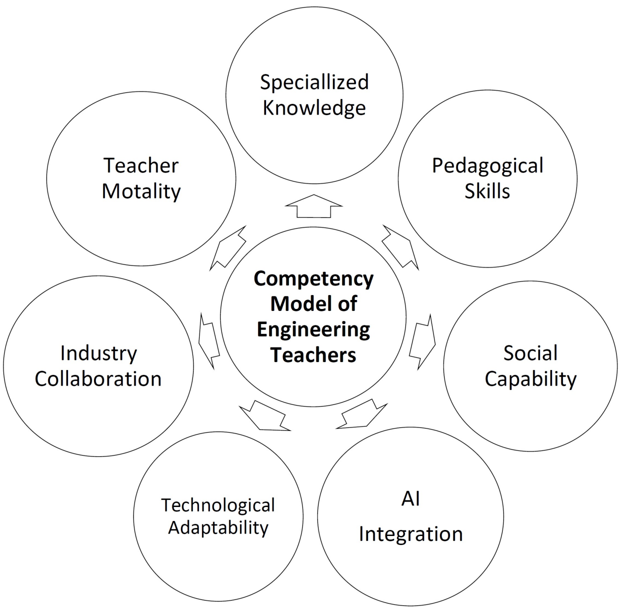

Figure 2. The competency model of engineering teachers

In conclusion, the proposed competency model offers a comprehensive approach to enhancing the qualifications of engineering educators in the AI-driven era. By addressing technical expertise, pedagogical strategies, and ethical considerations, the model prepares educators to train the next generation of engineers effectively. As industries and technologies evolve, continuous refinement of this framework will be essential to maintaining its relevance and effectiveness. Future research should focus on validating the model through empirical studies and exploring its application across diverse educational contexts.

DISCUSSION

The proposed competency model emphasizes the integration of AI, sustainability, and ethical practices in engineering education. By fostering interdisciplinary collaboration and leveraging advanced technologies, this model equips educators to address societal challenges and prepare students for dynamic career paths.

Enhancing faculty development

According to the American Society for Engineering Education (ASEE) and the National Academy of Engineering (NAE), the evolution of competency models is critical to developing an educational framework that produces exceptional engineers for the digital era. To achieve this goal, several key initiatives are recommended.

Augmenting the competency framework

Engineering faculty should regularly refine competency models to incorporate emerging trends and technologies. Examples include advancements in AI for predictive modeling, the Internet of Things (IoT) for smart manufacturing processes, and blockchain technology for enhancing data security in engineering projects. Emphasizing these technologies can better align educational frameworks with cutting-edge industry practices. This includes a focus on interdisciplinary collaboration, sustainability, and the integration of advanced technologies like AI and the IoT. By adapting the framework to address these areas, educators can ensure their teaching aligns with current industry demands.

Workshops and training programs

Faculty development programs must prioritize AI literacy, data analytics, and advanced computing techniques. Workshops, conferences, and online courses can serve as effective platforms for skill-building and knowledge dissemination, enabling educators to remain current in their fields. For example, workshops focusing on AI integration in engineering curricula or conferences addressing advancements in IoT technologies have demonstrated significant success in equipping educators with relevant skills. Similarly, online courses on data analytics and machine learning have provided accessible and flexible learning opportunities, empowering faculty to incorporate these competencies into their teaching methodologies.

Mentoring programs
Establishing mentoring initiatives can bridge gaps between part-time and full-time educators. These programs foster collaboration, facilitate the exchange of innovative teaching strategies, and support the professional growth of faculty members at all levels.

Industry collaboration
Strengthening partnerships with industry leaders is essential for ensuring that educators are aligned with technological advancements and professional standards. Notable examples include collaborations such as the joint initiatives between Massachusetts Institute of Technology (MIT) and major tech companies to develop AI-driven curricula and industry-sponsored hackathons at universities that provide real-world problem-solving opportunities for students and faculty. These collaborations enable educators to stay at the forefront of technological innovation and ensure the practical application of their teaching content. Collaborative projects and internships for faculty members can offer practical insights, enhance curriculum relevance, and provide opportunities for real-world application of engineering concepts.

Trends in engineering competencies for the AI era

The rapid advancement of technology requires a reevaluation of the competencies necessary for engineering educators. Several key trends have emerged.

Technical proficiency
Engineering educators must develop expertise in emerging fields such as AI, IoT, and data science. This proficiency ensures they can effectively teach the technical skills required for the Fourth Industrial Revolution and prepare students for dynamic career landscapes (Rotherham & Willingham, 2009).

Interpersonal skills
In addition to technical expertise, educators must possess strong interpersonal skills, including interdisciplinary collaboration, adaptability, and effective communication. These skills enable them to foster teamwork and drive innovation within diverse educational and engineering contexts.

Ethical and environmental responsibility
As engineering increasingly intersects with societal and environmental challenges, educators must emphasize the importance of sustainability and ethical practices. This includes instilling a mindset of accountability and social responsibility in students, ensuring they are equipped to make informed decisions about the broader implications of their work.

AI's integration into engineering practice significantly impacts how educators approach teaching. AI tools are transforming classrooms by enabling personalized learning experiences, automating administrative tasks, and streamlining instructional processes. For example, AI-driven tools like Coursera's adaptive learning algorithms help customize course content to meet individual learning needs. Similarly, platforms such as Gradescope automate grading and provide detailed feedback, while tools like Labster offer virtual lab environments for practical engineering experiments, making learning both efficient and engaging. Engineering educators must understand these tools, not only to improve their teaching efficiency but also to demonstrate practical applications to students. For instance, AI-driven adaptive learning platforms can tailor content to individual students' needs, enhancing engagement and retention.

Moreover, the role of AI in the development of new technologies underscores the importance of ethical education. As AI continues to evolve, engineers will encounter complex ethical dilemmas, such as bias in algorithms, data privacy concerns, and the societal consequences of automation. Educators must lead by example, integrating discussions of these issues into their curricula and fostering a culture of ethical responsibility.

One persistent challenge in engineering education is bridging the gap between classroom instruction and industry expectations. The proposed competency model addresses this gap by emphasizing not only academic knowledge but also professional development, ethical responsibility, and continuous learning. By aligning educational outcomes with industry needs, this model ensures that graduates are well-prepared to contribute effectively to the engineering profession.

Testing and validating the proposed model in diverse educational settings is a crucial next step. Pilot studies should involve collaboration with engineering faculties across various institutions to ensure broad applicability. These studies can be structured to include workshops, focus groups, and controlled classroom implementations to gather qualitative and quantitative data. Specific metrics, such as student engagement levels, learning outcomes, and the adaptability of educators to integrate AI tools, should be used to assess the model's effectiveness. Additionally, feedback from both educators and students can provide critical insights for refining the framework. Pilot studies with engineering faculties can help refine the model, evaluate its impact on teaching practices, and assess how it influences student outcomes. Such research would provide valuable insights into the model's effectiveness and highlight areas for further improvement.

CONCLUSION

This study proposes a synthesized and integrated competency model for engineering educators in the AI era. It bridges traditional technical and pedagogical competence with emerging ethical imperatives and AI literacy. The model offers a roadmap for engineering faculties seeking to modernize teaching practices and better prepare students for societal impact.

By implementing this integrated competency model, institutions can better align engineering education with the needs of Industry 5.0 and the Sustainable Development Goals (SDGs). The model fosters not only employability but also civic responsibility and adaptability, key attributes for the engineers of tomorrow. Future work will focus on longitudinal validation and refining the model across diverse cultural and institutional contexts.

DECLARATION

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Author contributions

Xu LH: Conceptualization, Data curation, Methodology, Resources, Writing—Original draft, Writing—Review and Editing. The author read and approved the final manuscript.

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Ethics approval

Not applicable.

Informed consent

Not applicable.

Conflict of interest

The authors declare no competing interest.

Use of large language models, AI and machine learning tools

No AI tool was used.

Data availability statement

No additional data.

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