Transforming engineering education through the Metaverse: design principles and essential competencies

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Abstract: *This paper explores the transformative potential of the metaverse in engineering education. The research methods include data collection by keywords from Google Scholar, Web of Science, Science Direct and IEEE xplore digital library. The analysis of the articles in the field are focusing on the design principles that underpin effective virtual learning environments and the essential competencies that future engineers must develop to thrive in this new paradigm. The key competencies for future engineers will blend traditional engineering skills with digital literacy, immersive technology proficiency, and collaborative problem-solving. The design principles for leveraging the full potential of the metaverse include: commitment and attention to user experience; curriculum alignment; accessibility and inclusion and changes in the assessment methods. Finally, we outline a metaverse for developing future engineers' competencies and integrating Virtual reality (VR) technologies into engineering curricula and highlight the benefits of hands-on experience with VR systems. This paper aims to provide educators, policymakers and industry leaders with insights that can be employed to design and implement educational programs which equip students with the requisite skills and knowledge to excel in an increasingly virtual and interconnected world.*

Keywords: engineering education, Metaverse, key competencies, design principles.

1. Introduction

Interdisciplinary engineering education (IEE) aims to train students to bring skills from different disciplines together in a single context (Van den Beemt et al., 2020). Future engineers need to be prepared with a new set of capabilities (Beagon et al., 2022), to use abstract and experiential learning, to work independently and in crews, and to balance engineering science and practice (Bordogna, 1997). Opportunity to meet the requirements for proper training that will fulfill the knowledge expectations of engineers in the imminent, holds the metaverse.

Metaverse proposed enormous advantages in engineering education (Singh et al., 2022). First, that is environment extended learning capabilities by 3D objects (Marmaridis & Griffith, 2009; Abraham et al., 2023). Second, the three-dimensional space of the metaverse can enhance the understanding of 3D objects and to make learning more interesting (Lee & Lee, 2022). In addition, in the metaverse invisible elements can be demonstrated, like electromagnetic and magnetic fields using

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metaverse 3D-virtual environment, which help the understanding and learning process of students (Lee & Lee, 2022).

"Relating to all Internet technologies, the Metaverse is an emerging environment that allows immersive interactive experiences to enhance comprehension. Combining Metaverse with constructivist learning, students can engage in engineering tasks and receive real-time feedback for deeper understanding." (Sidhuat al., 2024) The metaverse enhances realistic simulations and collaborative learning in engineering education, but it also presents challenges that require regulation and strong theoretical training to ensure effective integration. (Zaga, 2023) The study of (Al-kfairy & Alfandi, 2024) reveals significant ethical considerations, including privacy concerns, data security risks, and the widening digital divide, and proposes robust solutions including enhanced privacy protections, initiatives to bridge the digital divide, and frameworks to ensure safe and inclusive environments.

The article represents a study for proper criteria selection and constructing engineering education content for metaverse education by assessing available literature data.

2. Metaverse for engineer education

2.1 Key competencies for future engineers

There is no agreement on the technical framework of the Education Metaverse, and how to design the key elements (Chen et al., 2023).

The frame for future engineers' competencies is well described, demanding new skills and agility as abilities of deal with Artificial intelligence (AI) and digital tools. Sustainability is crucial in future engineering solutions (Moore 2024).

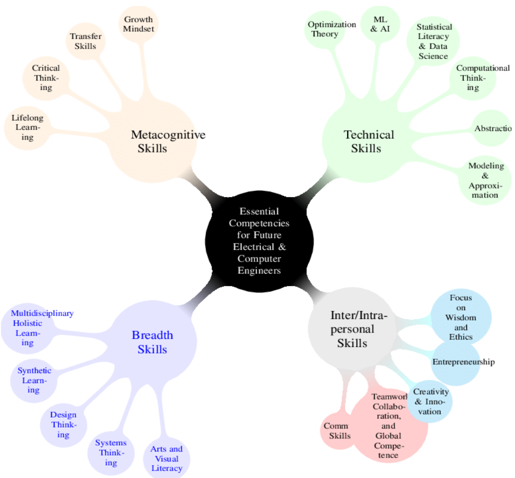

Figure 1. Essential Competencies for Future Electrical & Computer Engineers (Qadir et al. 2020)

On Figure 1 represents the essential competencies for Future Electrical & Computer Engineers by Qadir et al. (2020), that include physical layer, data layer, computational layer, interaction layer, and application layer. They organize these essential competencies in four areas: metacognitive skills, technical skills, breadth skills, and inter/intra-personal skills. Their work is timely as the electrical and computer engineering community needs a special focus on the essential competencies they have highlighted to thrive in the coming volatile, uncertain, complex, and ambiguous times.

In the metaverse and immersive reality, these competencies are needed by engineers of all professional fields.

New-age skills make a person receptive to world-class standards of safety and quality. In pending years engineers able to work in a diverse, multi-national, multi-disciplinary environment that sparks innovation and creative thinking will be in demand (Guven, 2020).

2.2 Design principles for effective Metaverse integration

Metaverse provides a platform where learners can interact with digital content and engage in collaborative projects in a more interactive and immersive manner (Meena et al., 2023).

Metaverse is not just an emerging new technology it builds on years of research in immersive interactivity and artificial intelligence and will significantly alter education (Meena et al., 2023).

There are three Design key elements (virtual avatars, virtual learning resources, and virtual teaching scenarios) in the Education Metaverse (Chen et al., 2023). The framework of a metaverse is given on Figure 2.

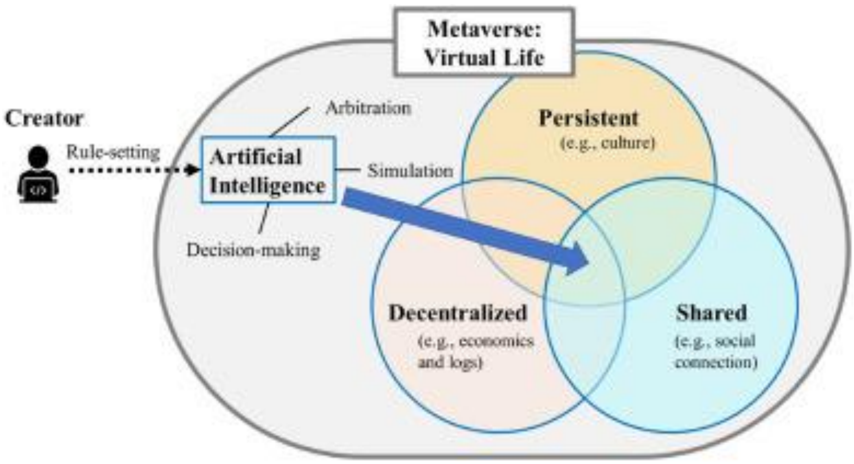

Figure 2. The framework of a metaverse (Hwang & Chien 2021)

Design principles play a crucial role in ensuring the effective integration of the metaverse into daily life. By applying concepts such as narrative composability, social assortativity, and path discoverability (Frydenberg & Ohri, 2023), designers can create immersive and interconnected experiences that enhance user engagement and facilitate seamless transitions between virtual locations. Additionally, the moral foundation for the metaverse emphasizes the importance of retaining valuable components of the physical world and prioritizing a deep connection with the natural world (Miah, 2022). Integrating the metaverse into various aspects of human life, such as education and transportation systems, requires a comprehensive understanding of design principles to optimize outcomes and user experiences. Educator training and broader involvement are also essential for effective integration into educational settings, emphasizing the promise of engaging students and reshaping teaching methodologies (Pahmi at al., 2023).

The design principles for effective metaverse integration can be considered in several aspects:

2.2.1 Commitment and attention to user experience

Ensuring the metaverse platform is intuitive and user-friendly is crucial for effective learning. The design principles should focus on:

Intuitive Navigation: The interface should be easy to navigate with clear instructions and minimal learning curve. This includes well-labeled buttons, easy-to-understand icons, and logical layout.

Consistent Design: The platform should maintain a consistent design language throughout, helping users to quickly become familiar with the environment.

Interactive Elements: Engaging, interactive elements such as drag-and-drop features, clickable objects, and real-time feedback can enhance the user experience.

Customizability: Allowing users to personalize their learning environment to suit their preferences can increase comfort and engagement.

Technical Support: Providing robust technical support, including tutorials, help centers, and real-time assistance, ensures users can resolve issues quickly and continue their learning without significant interruptions.

2.2.2 Curriculum alignment

Integrating metaverse activities with existing course objectives and content ensures that the learning experiences are relevant and effective. Key considerations include:

Educational Objectives: All metaverse activities should align with the overarching educational goals of the course. This ensures that time spent in the metaverse is productive and reinforces key concepts.

Seamless Integration: The metaverse content should be seamlessly integrated with traditional teaching methods. This could involve using the metaverse for simulations and practical exercises while lectures and theoretical discussions occur in conventional settings.

Modular Content: Designing metaverse content in modular formats allows instructors to easily incorporate relevant sections into their courses as needed.

Collaborative Learning: Facilitating group activities within the metaverse promotes collaboration and mirrors real-world engineering projects.

Feedback Loops: Continuous feedback from both students and educators should be used to refine and improve the integration of metaverse activities with the curriculum.

2.2.3 Accessibility and inclusion

Making the metaverse accessible to all students, including those with disabilities, ensures inclusivity and equal learning opportunities. Important aspects include:

Universal Design Principles: Implementing universal design principles ensures that the platform is usable by the widest range of people without the need for adaptation.

Assistive Technologies: The metaverse platform should be compatible with various assistive technologies such as screen readers, voice recognition software, and alternative input devices.

Multiple Interaction Modes: Providing multiple ways for users to interact with the metaverse, such as through voice commands, keyboard shortcuts, or touch interfaces, caters to different needs and preferences.

Clear Visuals and Audio: Ensuring that visuals are clear and audio is high-quality and adjustable helps students with visual and auditory impairments.

Inclusive Content: Designing content that is culturally sensitive and inclusive of diverse perspectives ensures that all students feel represented and engaged.

2.2.4 Assessment methods

Developing effective assessment techniques for metaverse-based learning activities is essential to measure student progress and learning outcomes accurately. Considerations include:

Formative Assessments: Regular, low-stakes assessments such as quizzes, interactive tasks, and in-world checkpoints help monitor student understanding and provide ongoing feedback.

Summative Assessments: High-stakes assessments like virtual exams, comprehensive projects, and presentations within the metaverse should evaluate the cumulative knowledge and skills acquired.

Performance Metrics: Utilizing in-built analytics to track student interactions, time spent on tasks, and progress can provide valuable insights into student performance.

Peer Assessment: Encouraging peer reviews and group assessments within the metaverse fosters collaborative learning and critical evaluation skills.

Reflective Assessments: Incorporating reflective practices such as journals, self-assessments, and debriefs allows students to evaluate their learning experiences and outcomes critically.

By focusing on these design principles, educators can ensure that the integration of the metaverse into engineering education is effective, inclusive, and aligned with educational objectives, ultimately enhancing the learning experience for all students.

3. Metaverse for development of future engineers' competencies

3.1 Key competencies for future engineers working in the Metaverse environment

Future engineers working in the Metaverse environment require key competencies such as proficiency in Metaverse technologies, including virtual reality (VR), augmented reality (AR), and blockchain (Gonzalez-Argote, 2022). They also need to possess strong engineering competencies tailored for future readiness, which can be developed through a Metaverse framework for engineering competency development comprising components like the Metaverse platform and engineering competency for future readiness (Thongprasit at al., 2022). Additionally, engineers in the Metaverse environment should have skills in collective intelligence, experiential learning, and the ability to participate in a continuous learning cycle to adapt to the evolving challenges of the 21st century (Abu Khousa at al., 2023). By integrating these competencies, future engineers can thrive in the digital transformation and contribute effectively to the development of innovative solutions within the Metaverse environment.

Summarizing the data and opinions from the various sources we can present some Key Competencies for future engineers working in the Metaverse environment in three aspects – Technical, Soft Skills and Digital Literacy.

Technical Skills: (1) VR Development Skills: Proficiency in VR content creation tools and programming languages (e.g., Unity, Unreal Engine, C#, Python). (2) 3D Modeling and Simulation: Ability to create and manipulate 3D models and simulations relevant to engineering problems. (3) Human-Computer Interaction (HCI): Understanding of ergonomics and usability to design effective VR interfaces and experiences. (4) Software and Hardware Integration: Skills in integrating VR software with various hardware components, such as sensors, haptic devices, and VR headsets.

Soft Skills: (5) Virtual Collaboration: Proficiency in collaborating with remote teams within virtual environments, utilizing VR for meetings, presentations, and joint problem-solving. (6) Visualization and Communication: Ability to convey complex engineering concepts through immersive visualizations and virtual demonstrations. (7) Innovative Thinking: Creativity in leveraging VR technologies to develop novel solutions and improve existing processes. (8) Design Thinking: Applying design thinking principles to create user-centric VR experiences and engineering solutions. (9) Adaptability: Flexibility to adapt to rapidly evolving VR technologies and methodologies. (10) Continuous Learning: Commitment to ongoing education and skills development in emerging VR technologies and engineering practices.

Digital Literacy: (11) Understanding and navigating digital environments, cyber-physical systems, and data analytics. (12) Domain-Specific Knowledge: Expertise in applying VR technologies within specific engineering domains (e.g., civil, mechanical, electrical, aerospace) for tasks such as prototyping, testing, and training. (13) Project Management: Skills in managing VR-related projects, including planning, execution, and evaluation. (14) Hands-On VR Experience: Practical experience in using VR equipment and software through internships, projects, and laboratory work. (15) Safety and Compliance: Knowledge of safety standards and compliance requirements related to VR systems and environments.

3.2 Benefits for adopting the Metaverse for educational purposes

Future engineers can adapt to the Metaverse environment by leveraging innovative concepts and technologies proposed in recent research. The Engineering Brain theory integrates the Metaverse concept into civil engineering, offering a new approach to enhance efficiency, safety, and sustainability in civil projects (Wang at al., 2022; Abraham, 2023). Additionally, the development of a metaverse framework for engineering competency focuses on utilizing the Metaverse to improve the engineering management system and train engineers to meet international standards, preparing them for the digital transformation ahead (Thongprasit at al., 2022). Furthermore, incorporating artificial intelligence (AI) within the Metaverse through deep learning and reinforcement learning techniques can address challenges in various applications, providing opportunities for transformative changes across industries and enhancing virtual interactions and environments (Ren, 2023). By embracing these advancements, future engineers can effectively navigate and thrive in the evolving Metaverse landscape.

The content for engineering education is constructed well, as algebra, calculus, and physics courses have significant effects, and their academic performance should be highly considered (Bautista et al., 2016). Computational thinking and programming skills are indispensable for future engineers (Qadir et al., 2020).

Using the metaverse to train engineers is a good way to get ready for the digital transformation happen in the future (Thongprasit & Piriyasurawong, 2022). Metaverse in education offers abundant benefits, services and tools that can be applied to improve the quality and access in education (Gonzales et al. 2023). Metaverse considered the next generation of social connections, and presents solution to the challenge in education. Benefits for adopting the metaverse for educational purposes (Hwang & Chien, 2021):

1) Place learners in a cognitive or skill practicing environment that could be risky or dangerous in the real world;

2) Set learners in the contexts to experience and learn what they generally do not have the opportunity to be involved in the real world;

3) Enable learners to perceive or learn something that requires long-term involvement and practice;

4) Inspire learners to try to create or explore something that they cannot afford to do in the real world owing to some practical reasons, such as the cost or the lack of real materials;

5) Allow learners to have alternative thoughts and attempts regarding their careers or lives;

6) Enable learners to perceive, experience, or observe things from different perspectives or roles;

7) Empower learners to learn to interact and even collaborate with people that they might not have opportunities to work within the real world;

8) Explore the potential or higher order thinking of learners by engaging them in complex, diverse, and authentic tasks.

4. Conclusion

Immersive virtual reality (VR) is revolutionizing various fields, including engineering. Future engineers need to develop a unique set of competencies to thrive in this environment. A brief overview of how the metaverse can transform engineering education, the key competencies required for future engineers, and the design principles for effective implementation.

By embracing the metaverse, engineering education can not only keep pace with technological advancements but also lead the way in cultivating a new generation of engineers who are proficient in utilizing cutting-edge tools to solve complex problems. The insights provided in this paper aim to guide educators, policymakers, and industry leaders in designing and implementing educational programs that equip students with the skills and knowledge needed to excel in an increasingly virtual and interconnected world.

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