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Transforming Engineering Roles and Education Through Industry 5.0 Enabling Technologies: A Narrative Review

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ABSTRACT

BACKGROUND & CONTEXT

The emergence of Industry 5.0 marks a new phase in industrial evolution, characterized by the convergence of advanced enabling technologies, such as AI, robotics, digital twins, 5G-6G, additive manufacturing, and nanotechnology, with a renewed emphasis on human-centricity, sustainability, and resilience. These transformations are redefining engineering roles and challenging the adequacy of traditional engineering curricula.

PURPOSE OR GOAL

This study aims to explore how Industry 5.0 enabling technologies are transforming engineering roles and to propose educational reforms that align engineering education with the competencies and responsibilities required in future workplaces.

APPROACH OR METHODOLOGY

This study adopted a targeted narrative review approach. Focusing on the functional competency “Proficiency in Enabling Technologies”, the study synthesized insights from 35 peer-reviewed articles (2020–2024) selected from a prior systematic review. Using the SAMR Model as the analytical lens, these articles were examined to determine how advanced digital tools, such as AI, robotics, and extended reality, reshape engineering work and education.

OUTCOMES

Key transitions in engineering roles were identified, including shifts from operators to orchestrators, specialists to systems integrators, technical experts to holistic engineers, and product developers to sustainability stewards. Emphasis is placed on holistic competency development, interdisciplinary adaptability, professional identity formation, and ethical responsibility. The study recommends embedding AI-driven design studios, collaborative robotics training, digital twin practicums, and sustainability-focused workshops into curricula.

CONCLUSIONS

Engineering education must evolve beyond technical training to encompass systems thinking, human-centric design, and sustainable innovation. Curricular reforms should be informed by the dynamics of future engineering work as shaped by Industry 5.0 technologies. This study offers a structured framework that can inform curricular innovations and support ongoing pedagogical shifts in engineering education.

KEYWORDS

Industry 5.0, Engineering Education, Enabling Technologies, Digital Transformation, Curriculum

Introduction

Successive industrial revolutions, each reshaping economies, societies, and workforces, have marked technological evolution. As we transition from Industry 4.0 to Industry 5.0, a fundamental paradigm shift is occurring—from a technology-centric model focused on automation and cyber-physical systems to a human-centric framework emphasizing collaboration between humans and intelligent systems (Adel, 2022). Unlike Industry 4.0, which prioritized efficiency and digital transformation, Industry 5.0 integrates human intelligence with advanced technologies, fostering sustainability, resilience, and inclusivity in industrial and engineering practices (Breque et al., 2021; Xu et al., 2021).

At the heart of Industry 5.0 lies the concept of human-machine collaboration, where humans and AI-powered technologies work symbiotically to enhance productivity and innovation rather than replace human labor (Nahavandi, 2019). The European Commission (2021) outlines Industry 5.0's core pillars—human-centricity, sustainability, and resilience—which redefine the role of engineers in designing, implementing, and overseeing emerging technologies. These technologies, including human-robot collaboration, artificial intelligence, digital twins, bio-inspired computing, and energy-efficient systems, are poised to transform engineering work, requiring a recalibration of skills and competencies (Maddikunta et al., 2022; World Economic Forum, 2023).

The rapid technological progress necessitates a reassessment of engineering education. Historically, industrial revolutions have influenced educational frameworks to ensure the workforce remains adept at leveraging new technologies (Lantada, 2020). In the context of Industry 5.0, engineering curricula must evolve to equip graduates with both technical expertise and human-centric skills, such as cognitive flexibility, ethical responsibility, and socio-technical integration (Carayannis & Morawska-Jancelewicz, 2022). To meet these demands, a systematic review was conducted to identify the future engineering competencies required in Industry 5.0 (Fernando et al., 2025). A key finding from this review is the importance of *Proficiency in Enabling Technologies*, which refers to the ability to leverage cutting-edge innovations to optimize operations and address complex engineering challenges. This highlights the need for a deeper investigation into Industry 5.0's evolving work demands in engineering and its impact on the future of engineering education.

Given these considerations, this study seeks to address two critical research questions:

1. How do Industry 5.0 enabling technologies transform engineering work?
2. How can engineering curricula evolve to address Industry 5.0 workplace demands?

Materials and Methods

This study employed a targeted narrative review as part of a broader research initiative to develop a holistic engineering competency model and an Industry 5.0-ready engineering curriculum framework. Specifically, this study focused on the functional competency “Proficiency in Enabling Technologies” to examine how advanced digital tools such as artificial intelligence (AI), robotics, and extended reality transform engineering practice and education.

Materials

To examine how advanced technologies transform engineering practice and education, this study synthesized insights from the 35 peer-reviewed articles that were part of a larger systematic review, which initially established “Proficiency in Enabling Technologies” as a functional competency. These articles, published between 2020 and 2024, were selected because they focus on enabling technologies within the context of Industry 5.0 and engineering. Table 1 presents the summary of 10 enabling technologies and their distribution across the reviewed literature.

Table 1: Enabling Technologies in Industry 5.0 Literature

Technology	References																																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	
Artificial Intelligence																																				
Collaborative Robots																																				
Industrial IOT																																				
Digital Twin/Triplet																																				
Extended Reality																																				
Sensors																																				
Distributed Computing																																				
Additive Manufacturing																																				
5G-6G Wireless Comm.																																				
Nanotechnology																																				

Legend: 1. Alimam et al. (2023), 2. Balogh et al. (2023), 3. Barbieri et al. (2021), 4. Bharathi et al. (2023), 5. Blinova et al. (2024), 6. Broo et al. (2022), 7. Carayannis & Morawska-Jancelewicz (2022), 8. Dehbozorgi et al. (2024), 9. Eriksson et al. (2022), 10. Ghani (2022), 11. Habash (2022), 12. Hansen et al. (2023), 13. Hazrat et al. (2023), 14. Javed et al. (2023), 15. Lagorio & Cimini (2024), 16. Lattanzio et al. (2022), 17. Leberuyser et al. (2024), 18. Lober et al. (2022), 19. Montini et al. (2022), 20. Nagy et al. (2022), 21. Nagy et al. (2024), 22. Oeij et al. (2024), 23. Pang et al. (2023), 24. Pavličková et al. (2024), 25. Pinto et al. (2024), 26. Rapitsenyane et al. (2023), 27. Ruppert et al. (2023), 28. Salminen et al. (2023), 29. Schürle et al. (2023), 30. Seno et al. (2023), 31. Sikora et al. (2023), 32. Singh & Alhabbas (2024), 33. Tu et al. (2023), 34. Vidric et al. (2023), 35. Zhao et al. (2023)

Data Extraction and Analysis

This study adopted the SAMR Model (*Substitution, Augmentation, Modification, Redefinition*) as an analytical framework to classify the impact of enabling technologies on engineering workflows. Originally developed by Dr. Ruben Puente-dura (n.d.) for assessing technology integration in education, the SAMR Model categorizes technological applications into four levels, as illustrated and defined in Figure 1. These levels are further grouped into two overarching categories: *Enhancement* (Substitution and Augmentation) and *Transformation* (Modification and Redefinition).

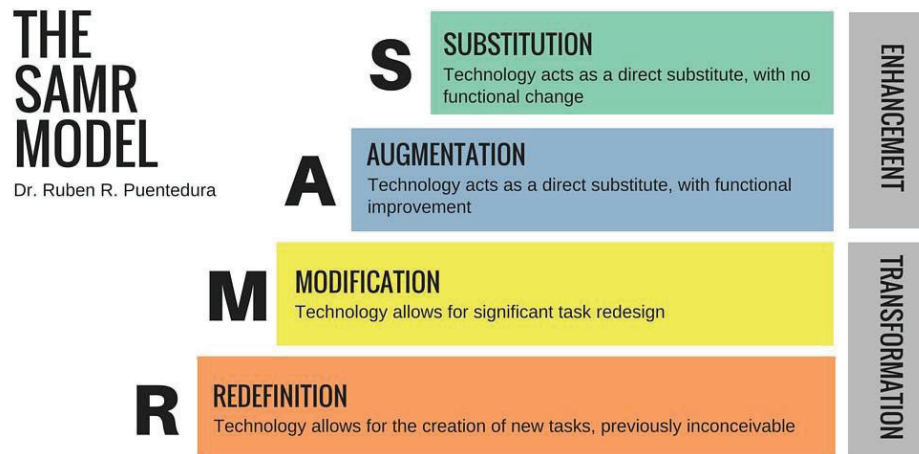


Figure 1: The SAMR Model

This study applied the SAMR analysis to systematically evaluate how each enabling technology modifies engineering work, ranging from incremental digital enhancements to radical shifts in practice. By classifying these changes, the study identified trends in technological adoption and their influence on engineering tasks, decision-making, and collaboration.

Building upon the findings of the SAMR analysis, a subsequent review of contemporary literature was conducted to propose the necessary transformations in future engineering education. This additional layer of analysis aligns educational advancements with the evolving nature of engineering practice, ensuring that engineering curricula evolve in response to emerging technological paradigms.

Results and Discussion

Transforming Engineering Work

Industry 5.0 marks a shift from the automation-driven focus of Industry 4.0 to a human-centric, sustainable, and resilient industrial ecosystem. By applying the SAMR model to synthesize 35 Industry 5.0-focused peer-reviewed papers, 118 distinct applications across 10 core enabling technologies were identified, revealing significant trends in the transformation of technologies. As shown in Table 2, the results indicated a strong prevalence of *Redefinition* (43%) and *Modification* (38%) in the future of engineering work due to these technologies.

Table 2: Distribution of Industry 5.0 Enabling Technologies Across SAMR Levels

SAMR Level	Frequency	Dominant Technologies
Redefinition (R)	43% (51/118)	Digital Twins/Triplets, Extended Reality, Additive Manufacturing, Nanotechnology
Modification (M)	38% (45/118)	Distributed Computing, Collaborative Robots, Industrial Internet-of-Things
Augmentation (A)	19% (22/118)	Artificial Intelligence, Sensors, 5G-6G Wireless Communication
Substitution (S)	0% (0/118)	None

Redefinition-level, which accounts for 51 of the 118 applications analyzed, introduces entirely new capabilities that were previously unattainable. Examples include nanotechnology's cellular-level medical interventions (Pang et al., 2023), digital twins enabling real-time simulation of entire factories (Alimam et al., 2023; Hazrat et al., 2023; Montini et al., 2022; Ruppert et al., 2023), and enhanced training and learning through immersive learning scenarios (Hazrat et al., 2023; Oeij et al., 2024). *Modification*, representing 45 applications, significantly restructures industrial processes without completely redefining them. Notable instances include IIoT for increased interoperability and connectivity (Barbieri et al., 2021; Javed et al., 2023; Schürle et al., 2023; Singh & Alhabbas, 2024) and increased flexibility and adaptability in manufacturing through reprogrammable cobots (Bharathi et al., 2023; Hansen et al., 2023; Nagy et al., 2024). The dominance of *Redefinition* and *Modification* highlights that Industry 5.0 technologies prioritize systemic innovation over incremental efficiency improvements.

The study also found that only 19% of applications focus on *Augmentation*, where technologies improve efficiency without significantly altering workflows. These applications are primarily seen in sensor technologies, which enhance real-time monitoring (Blinova et al., 2024; Ruppert et al., 2023), and AI, which speeds up data analysis and interpretation (Pavlíčková et al., 2024) and detects anomalies faster than humans in safety-critical systems (Schürle et al., 2023). In contrast to Industry 4.0, which emphasized predictive maintenance and automation-driven efficiency gains, Industry 5.0 focuses on human-machine symbiosis (*Redefinition*) and resilience-oriented technological frameworks (*Modification*).

A notable analysis result was the complete absence of *Substitution* (0%), a prevalent trend in Industry 4.0, such as replacing paper-based manuals with digital alternatives. This absence aligns with Industry 5.0's emphasis on higher-order integration, where human-AI collaboration necessitates redefined roles and sustainable technologies require process modifications. For instance, collaborative robots leveraging gesture control redefine human-machine interaction (Bharathi et al., 2023; Nagy et al., 2024; Zhao et al., 2023), while additive manufacturing (AM) modifies traditional supply chains by reducing material waste and decentralizing production (Rapitsenyane et al., 2023; Serio et al., 2023).

As shown in Figure 2, the radial plot further illustrates the systemic transformation of Industry 5.0 enabling technologies, highlighting how they contribute across different levels of digital innovation. While certain technologies are expected to redefine engineering work the most, the visualization emphasizes that each technology also exhibits characteristics of other SAMR levels, indicating a continuum of transformation rather than rigid classifications.

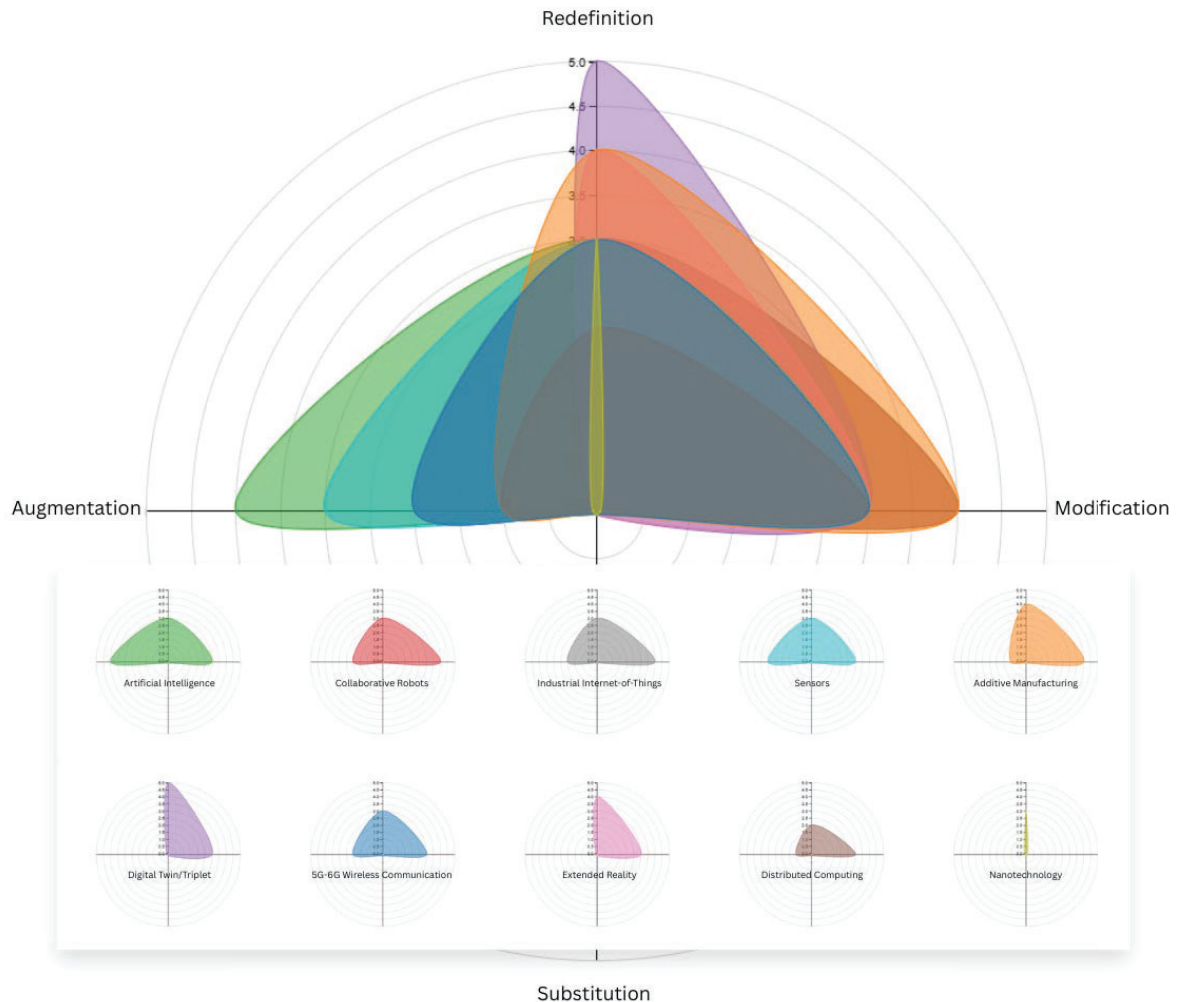


Figure 2: Radial Plot of Impact of Industry 5.0 Enabling Technologies on Future Engineering Work

The visualization shows that most Industry 5.0 technologies span multiple SAMR levels, reinforcing the idea that their impact is gradual and multidimensional. Technologies such as AI, 5G-6G Wireless Communication, and Sensors have a strong presence in both the *Augmentation* and *Modification* categories, demonstrating their role in enhancing efficiency, enabling real-time data exchange, and improving decision-making before achieving more transformative applications. Similarly, Digital Twins/Triplets, Additive Manufacturing, Extended Reality, and Collaborative Robots are positioned between *Modification* and *Redefinition*, indicating their potential to redefine manufacturing and automation.

Ultimately, this radial plot reinforces that Industry 5.0 technologies are not static innovations but dynamic forces of systemic transformation. While some technologies exhibit the strongest potential for redefining engineering work, their impact is realized through a progressive, interconnected evolution across all SAMR levels. The transition to Industry 5.0 requires

integrative, forward-thinking strategies that acknowledge the fluidity of technological adoption and the need for holistic transformation rather than isolated advancements.

Table 3 summarizes the transformation in engineering work and roles analyzed through the SAMR model. It demonstrates how emerging technologies fundamentally reshape engineering work by operating primarily at the Modification and Redefinition levels rather than simply *Substitution* or *Augmentation*. AI, cobots, and XR exemplify *Redefinition* by creating unprecedented human-machine collaboration paradigms, shifting engineers from operators to orchestrators of AI-assisted systems, while IIoT and digital twins showcase *Modification* through systemic workflow restructuring that replaces linear processes with dynamic, simulation-driven approaches. Nanotech and 5G/6G introduce *Redefinition*-level capabilities (e.g., cellular-scale engineering), spawning hybrid roles demanding new competencies. In contrast, sustainability-driven technologies like additive manufacturing modify traditional objectives by embedding circular design principles. Crucially, the absence of *Substitution*-level changes underscores that Industry 5.0's transformation is not about automating old tasks but reimagining work through human-centric innovation, requiring educators and industries to prioritize higher-order skills aligned with these disruptive SAMR tiers, where technology does not just enhance but redefines what engineering work entails.

Table 3: Paradigm Shifts in Engineering Practice for the Industry 5.0 Era

Transformation	Change in Workflow	Change in Engineers' Role
Human-Machine Collaboration	From manual to AI-assisted design	From operators to orchestrators
Systemic Workflow Restructuring	From linear to iterative and simulation-driven workflow	From specialists to systems integrators
New Capabilities & Job Roles	From discipline-specific to holistic competencies	From technical experts to holistic engineers
Sustainability & Resilience	From performance-based to human-centric design	From product developers to sustainability stewards

Transforming Engineering Education

To meaningfully respond to Industry 5.0, engineering education must adopt enabling technologies and redesign teaching strategies to reflect how these tools reshape student learning. While the SAMR model helped assess the level of transformation technology brings to engineering work, its educational impact requires grounding in established educational theories. Constructivist principles, for instance, emphasize active knowledge construction through real-world problem-solving. This is seen in agile engineering labs, where students iteratively prototype and refine solutions in sprint cycles—mirroring real industry workflows. Experiential learning theories like Kolb's call for learning through concrete experiences and reflection. This justifies approaches like mentored industry placements and failure analysis workshops that situate students in authentic, complex engineering contexts. Lastly, socio-technical systems thinking recognizes the interplay between human, social, and technological components. For example, ethics clinics encourage students to explore how AI deployment impacts social systems, prompting critical reflection and responsible design decisions. These theoretical underpinnings ensure that technology-enhanced learning experiences are not only innovative but also meaningful, inclusive, and aligned with the human-centric vision of Industry 5.0. These and other recommended changes are summarized in Table 4.

Table 4: Transforming Engineering Education for Industry 5.0 Workforce Evolution

Engineers' Role	Recommended Changes
From operators to orchestrators	Augmented design studios. Integrate generative AI tools (e.g., Autodesk Fusion 360 with AI) where students learn to guide, evaluate, and refine AI-generated solutions while maintaining human oversight of critical decisions, e.g., Yoo et al. (2021). Cobot training programs. Offer hands-on training in collaborative robotics programming, safety protocols, and ergonomic workspace design using industry-standard platforms, e.g., Wolffgramm et al. (2021). Ethics clinics. An approach where students analyze real-world case studies of AI implementation failures and develop governance frameworks for responsible technology deployment, e.g., Martin et al. (2021).
From specialists to systems integrators	Digital twin practicums. Require students to create and maintain virtual replicas of physical systems throughout product lifecycles, using modelling and simulation tools, e.g., Liljaniemi & Paavilainen (2020). Agile engineering labs. Adapt software development methodologies to physical system design, with sprint-based projects incorporating rapid prototyping and continuous validation, e.g., Pineida & Dominguez (2023). Failure analysis workshops. Involve students in analyzing system breakdowns in simulated Industry 5.0 environments to develop resilience thinking.
From technical experts to holistic engineers	Disciplinary foundations. Maintain rigorous core programs in traditional engineering disciplines, e.g., Pacher et al. (2023). Holistic competency development. Weave through the curriculum high-order, interdisciplinary, adaptive competencies (e.g., data fluency, systems thinking, human factors) (Fernando et al., 2025). Professional identity development. Strengthen engineering identity in the context of Industry 5.0, e.g. Cooke et al. (2023) and Smit (2023), through: • Reflection portfolios for holistic growth (e.g., tracking the lifecycle consequences of design decisions through ethical, environmental, and social constraints) • Mentored industry placements (e.g., immersions with companies pioneering zero-waste manufacturing) • Professional practice courses as transformative experiences (Role-playing negotiations between competing stakeholder values)
From product developers to sustainability stewards	Circular design standards. Embed standards throughout the curriculum using frameworks like Cradle to Cradle certification requirements, e.g., Brunell et al. (2021). Regenerative design studios. Partner with local industries on real-world challenges with measurable sustainability targets, e.g., Hitt et al. (2025). Lifecycle analysis labs. Equip students with comprehensive environmental impact assessment tools, e.g., Gregory & Salado (2024).

Conclusion

This study examined how Industry 5.0 technologies reshape engineering work and the implications for engineering education. These technologies primarily drive changes at the Modification and Redefinition levels of the SAMR model, redefining engineering roles through enhanced human-machine collaboration, simulation-driven workflows, holistic competencies, and a stronger focus on sustainability. Engineering education must shift from siloed technical training to integrative, experiential learning emphasizing systems thinking, ethical awareness, and adaptability. The study expands the use of the SAMR framework to analyze workforce

transformation and offers practical guidance for curriculum modernization. While the proposed reforms provide a foundation for aligning education with Industry 5.0, further research is needed to validate their effectiveness and explore social and organizational dynamics.

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