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The Future Role of Mechanical Engineers in Virtual Reality: Opportunities, Challenges, and Future Perspectives

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Abstract: Virtual Reality (VR) has emerged as a transformative technology that is transforming engineering practices across various industries. In mechanical engineering, VR is increasingly utilized for product design, virtual prototyping, manufacturing process optimization, maintenance planning, safety training, and engineering education. This paper explores the evolving role of mechanical engineers in the era of virtual reality by examining its current applications, emerging opportunities, key challenges, and future prospects. The study is based on a review of recent scientific literature, industry reports, and technological developments related to VR and Industry 4.0. The findings indicate that VR enables engineers to improve design accuracy, reduce development costs, enhance collaboration, and create safer and more efficient working environments. However, several challenges remain, including high implementation costs, hardware limitations, cybersecurity concerns, and the need for specialized skills. Looking ahead, the integration of artificial intelligence, digital twins, haptic technologies, and Industry 5.0 is expected to further expand the role of mechanical engineers in immersive digital environments. The paper concludes that VR will become an essential component of future mechanical engineering, requiring engineers to continuously develop digital competencies alongside traditional engineering knowledge.

Keywords: Virtual Reality (VR), Mechanical Engineering, Industry 4.0, Digital Twin, Engineering Education, Product Design, Artificial Intelligence.

Introduction

Mechanical engineering has always depended on the engineer's ability to visualize systems that did not yet physically exist a mechanism's motion, the stress distribution inside a housing, the airflow around turbine blades [1]. For most of the twentieth century, this visualization happened on paper and, later, on a two-dimensional computer screen through computer-aided design (CAD) software. Virtual reality (VR) changes this relationship by allowing the engineer to step inside the model [2].

One of the earliest large-scale accounts of this shift is Berg and Vance, whose industry survey described VR as a decision-making tool used primarily for design evaluation in engineering-focused businesses, at a time when immersive hardware was still expensive and far from standardized [3]. Berni and Borgianni later systematized this growing body of work, reviewing 86 sources on VR in engineering and product design and organizing them by the design function they support, the VR technologies used, and the stage of the product lifecycle involved showing that VR's role extends well beyond a single design phase [4].

More recent studies provide direct, measurable evidence from mechanical engineering classrooms. A 2025 study at the University of New South Wales trained 17 undergraduate mechanical engineering students on the hand lay-up process in composite manufacturing, comparing VR-based instruction with conventional physical-lab instruction in a within-subjects experiment (Education Sciences) [5]. The results were mixed rather than uniformly positive: procedural accuracy was comparable between the two methods, and VR significantly reduced mental and physical workload as measured by NASA-TLX scores, yet it also produced higher frustration, driven mainly by navigation difficulties and motion discomfort, and took students longer to complete the task [6]. Despite this, qualitative interviews showed a strong student preference for VR because of its hazard-free, repeatable, and step-by-step nature. This nuance is important: it suggests VR's educational benefit is real but not unconditional [7].

A related but distinct line of work uses augmented reality (AR) rather than full VR. Pàmies-Vilà, Puig-Ortiz, and Jordi Nebot, of the Universitat Politècnica de Catalunya, developed a Unity-based AR application to teach Mechanism and Machine Theory on mobile devices, aiming to replace costly physical mechanism models with accessible 3D visualizations illustrating that immersive technology in mechanical engineering education is not limited to headset-based VR alone [8].

Taken together, this literature suggests two things relevant to this paper. First, VR (and the closely related AR) has already moved past the experimental stage in specific areas of mechanical engineering practice, particularly design review and technical training [9]. Second, the evidence is more nuanced than popular accounts suggest VR reduces some forms of workload while introducing others, such as frustration and slower task completion meaning claims of VR's benefits should be stated with their limitations attached. This paper builds on these findings to examine the opportunities VR creates for mechanical engineers (Section 3), the challenges limiting its adoption (Section 4), and where the technology and profession appear to be heading (Section 5) [10].

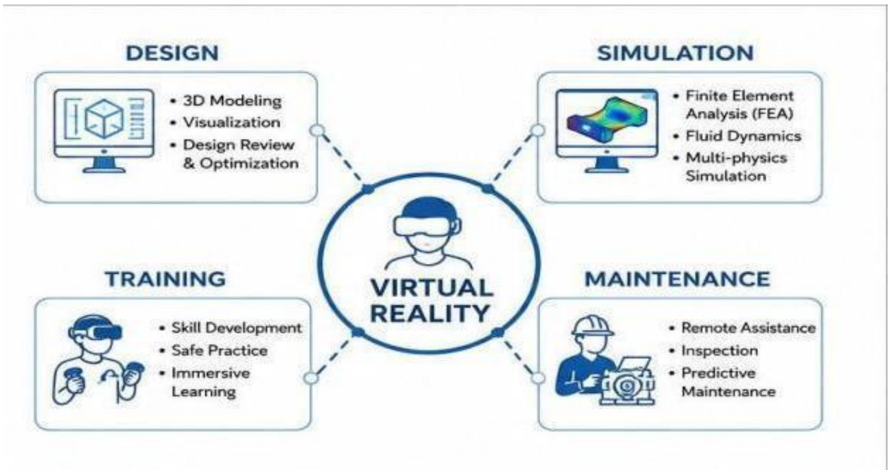

Figure 1. Conceptual framework of Virtual Reality applications in mechanical engineering.

Methodology

This paper adopts a narrative literature review approach, appropriate for synthesizing an emerging and interdisciplinary topic where the volume of directly comparable empirical studies is still limited. Rather than a systematic review with a fixed protocol, the goal was to identify representative, high-quality sources across three areas relevant to the research questions: industrial applications of VR in mechanical engineering, VR-based engineering education, and adoption barriers to immersive technologies in industry.

Search Strategy and Sources

Sources were identified through searches of academic databases and publisher platforms (including MDPI, Springer, SAGE, ScienceDirect, and Google Scholar) using combinations of the terms “virtual reality,” “mechanical engineering,” “product design,” “digital twin,” “Industry 4.0,” “Industry 5.0,” and “engineering education.” Priority was given to peer-reviewed journal articles published between 2017 and 2025, with an emphasis on studies from 2020 onward to reflect the current state of VR hardware and software capability. Foundational earlier studies (e.g., Berg & Vance, 2017) were retained where they remain the primary source for a specific claim about the history of industrial VR adoption.

Inclusion Criteria

The selected literature was evaluated according to three criteria: Relevance the source had to directly address VR or AR applications within mechanical engineering, product design, manufacturing, or engineering education, rather than immersive technology in general; Credibility priority was given to peer-reviewed journal articles and conference proceedings from recognized publishers (MDPI, Springer, SAGE, ScienceDirect, IEEE), with industry reports used only to support market-trend claims; Recency sources published between 2017 and 2025 were prioritized, with particular weight given to studies from 2023 onward to reflect current-generation VR hardware and adoption levels.

Limitations of the Review Approach

As a narrative rather than systematic review, this paper does not claim to be an exhaustive survey of all published VR-engineering literature, and source selection involved a degree of judgment regarding relevance and quality. Where a claim rests on a single study, this is noted explicitly rather than generalized as a settled finding, since replication across larger and more diverse samples is still needed.

Results and Discussion

Opportunities for Mechanical Engineers in Virtual Reality

Product Design and Virtual Prototyping

What happens when an engineer can walk around a design that does not physically exist yet? Long before VR headsets became affordable, engineering firms were already using the technology exactly this way catching clearance, ergonomic, and assembly problems inside a virtual model before a single physical prototype was machined [11]. What has changed since then is scope, not principle: VR now touches nearly every stage of the product lifecycle, from rough concept sketches to final manufacturing validation, not just the polished design-review meeting. The practical payoff is speed a virtual prototype can be reshaped and re-evaluated in minutes, which matters enormously when the alternative is machining a new physical part every time a design assumption turns out wrong [12].

Figure 2. VR in product design and virtual prototyping: a typical workflow cycle.

Simulation and Digital Twins

The industrial digital-twin and extended-reality market has been valued at tens of billions of dollars and is projected to grow substantially over the coming decade, with predictive maintenance and remote monitoring not entertainment identified as leading growth drivers. Pair VR with a digital twin a live, sensor-fed replica of a real machine and the technology stops being a design tool and starts being an operations tool [13]. A recent university project makes this concrete: researchers scanned a physical engine, rebuilt it as a live 3D model wired to real sensors, and let several people wearing headsets watch it run and even simulate faults from a safe distance. Less time reading gauges on the factory floor, more time interpreting the same data inside a shared virtual space [14].

Training and Skills Development

Picture two groups of engineering students learning the same hands-on manufacturing process one in a physical lab, one in VR. That comparison has actually been run. The VR group reported meaningfully lower mental strain, physical strain, and effort than the physical-lab group but also more frustration, mostly from fighting the controls and mild motion discomfort, and they took longer to finish. Their accuracy, however, ended up about the same either way. The lesson isn't that VR training is simply “better” it trades one kind of difficulty for another, and any curriculum built around it should expect that rather than be surprised by it. A similar instinct swap an expensive, fragile physical teaching aid for something students can hold via a phone screen shows up in augmented reality too, where mobile apps now let students manipulate mechanism models that used to require costly physical kits [15].

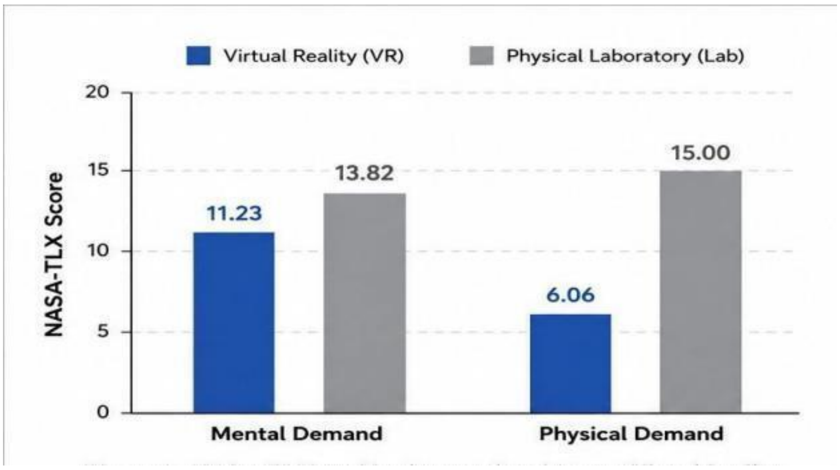

Figure 3. NASA-TLX workload comparison between Virtual Reality (VR) and physical laboratory environments.

Remote Collaboration and Maintenance Support

Imagine a specialist in one country guiding a repair on a machine in another, both looking at the exact same live 3D model in real time. This is no longer hypothetical the multi-user digital-twin setup described above works this way by design, letting people in different physical locations inspect the identical live equipment at once. Flying an expert across the world to fix a machine is slow and expensive; letting them look through someone else's headset is neither.

Career Positioning for Mechanical Engineers

For an engineer just entering the field, this adds up to a practical question: which skill is worth learning first CAD-to-VR workflows, simulation interpretation, or immersive-training design? All three are in active demand, and engineers who pick up even one have an edge in industries automotive, aerospace, advanced manufacturing that are already spending real money on this technology rather than just experimenting with it.

Challenges of Virtual Reality in Mechanical Engineering

Beyond the Price Tag: The Cost of Adoption

What prevents many companies from embracing Virtual Reality despite its well-documented advantages? In most cases, the answer is not a lack of interest but the financial commitment required for implementation. High-performance VR headsets, powerful computing hardware, specialized software, and employee training involve considerable upfront costs. For large manufacturing companies, these investments can often be justified by long-term improvements in productivity, product quality, and reduced development time. However, small and medium-sized enterprises frequently face budget constraints and uncertainty regarding return on investment, making VR adoption a difficult strategic decision. As a result, the high cost of implementation remains one of the most significant barriers to the widespread use of VR in mechanical engineering.

Technical Limitations and System Performance

Can a virtual environment perfectly reproduce every real-world engineering process? Despite remarkable technological progress, the answer is still no. Current VR systems may expose users to motion sickness, visual fatigue, and discomfort during prolonged sessions. Studies comparing VR-based and conventional laboratory training have also reported higher frustration levels among VR users, mainly due to navigation difficulties and motion-related discomfort. Furthermore, rendering delays, tracking inaccuracies, and the substantial computational power required for high-fidelity simulations can reduce the realism and effectiveness of virtual engineering environments. These technical limitations continue to challenge the broader adoption of VR in complex mechanical applications.

Data Security and Cyber Risks

As Virtual Reality becomes increasingly integrated with cloud computing, Internet of Things (IoT) technologies, and digital twins, cybersecurity has emerged as a critical concern. Engineering organizations now exchange large volumes of sensitive design files, manufacturing data, and real-time operational information through interconnected digital platforms. Unauthorized access, cyberattacks, or data breaches may lead to financial losses, intellectual property theft, and operational disruption. Consequently, ensuring robust cybersecurity measures and protecting data privacy have become essential requirements for the successful implementation of VR technologies in modern mechanical engineering.

The subsections above outline the individual barriers to VR adoption; Figure 4 summarizes their relative severity as assessed in this review, before turning to the human and organizational dimension of adoption.

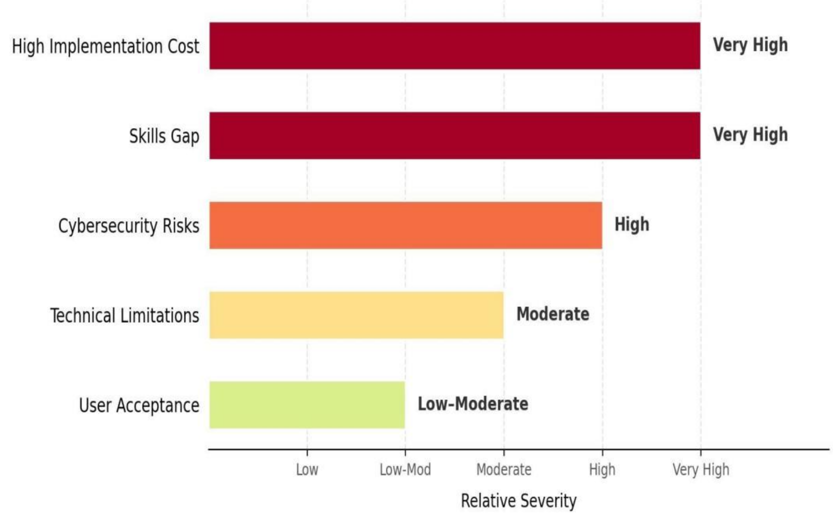

Figure 4. Relative severity of the major barriers to VR adoption in mechanical engineering, based on this review.

Human Acceptance and Organizational Change

Even the most advanced technology cannot deliver value if people are unwilling to use it. Many engineers remain cautious about replacing familiar workflows with immersive virtual environments, particularly when new interfaces require additional training or changes to established practices. Research on digital transformation consistently shows that organizational readiness, management support, and employee engagement are just as important as technological capability. A comprehensive review of human factors in VR for Industry 5.0 settings similarly argues that comfort, trust, and presence need standardized measurement before organization-wide rollouts can be evaluated fairly [10]. Therefore, successful VR implementation depends not only on improving hardware and software but also on developing user confidence through education, collaboration, and gradual organizational change.

SWOT Analysis

Table 1 summarizes the strengths, weaknesses, opportunities, and threats identified across the preceding subsections.

Table 1. SWOT analysis of Virtual Reality adoption in mechanical engineering.

Strengths	**Weaknesses**
• Fast, iterative design and prototyping • Improved workplace and training safety	• High upfront implementation cost • Motion sickness and physical discomfort
Opportunities	**Threats**
• Integration with artificial intelligence • Alignment with Industry 5.0 adoption	• Cybersecurity and data-breach exposure • Shortage of specialized VR/engineering skills

Overall, the challenges associated with Virtual Reality should not be viewed as obstacles that limit its future, but rather as opportunities for technological improvement and organizational innovation. Addressing these issues through continued research, investment, and workforce development will play a crucial role in accelerating the adoption of VR across the mechanical engineering sector.

Future Perspectives

AI-Powered Virtual Engineering

When artificial intelligence is integrated with Virtual Reality, mechanical engineers will be able to evaluate multiple design alternatives within a single virtual environment, thereby reducing development time and improving design accuracy. A 2025 systematic review of generative AI combined with extended reality maps out how AI-driven content generation is beginning to merge with immersive platforms, pointing toward VR environments that can propose and refine design variants on demand rather than only displaying them. As a result, engineers will make faster and more informed engineering decisions, which can increase productivity and minimize costly design errors.

Industry 5.0 and Human–Machine Collaboration

As manufacturing systems continue to evolve toward Industry 5.0, collaboration between humans and intelligent technologies is expected to become increasingly important. Instead of replacing engineers, Virtual Reality and AI will support human creativity and decision-making, allowing professionals to interact with smart machines in immersive environments while maintaining control over complex engineering tasks. Early examples of this shift are already visible outside product design: Industry 5.0-oriented welding-training frameworks that combine VR with human-centered instructional design are being piloted as a template for other skilled trades.

Sustainable Engineering and Green Manufacturing

One of the most promising future contributions of Virtual Reality lies in sustainable manufacturing. By reducing the need for repeated physical prototypes and extensive material testing, VR can help decrease resource consumption and production waste. Early framework studies combining virtual prototyping with life-cycle assessment report meaningful reductions in carbon emissions, energy consumption, and material waste compared with conventional prototyping across automotive, electronics, and consumer-product case studies, though this evidence base is still small and would benefit from independent replication before the specific percentages are treated as generalizable. Consequently, companies may achieve more environmentally responsible manufacturing processes while also lowering development costs.

Future Skills for Mechanical Engineers

Future mechanical engineers will need a combination of traditional engineering knowledge and advanced digital competencies. Skills in Virtual Reality, digital twins, artificial intelligence, and data analytics are likely to become essential as industries increasingly rely on interconnected technologies. Tactile feedback is one such emerging competency area: an early-stage haptic VR simulator built for shielded-metal-arc-welding (SMAW) training illustrates how touch-based feedback is beginning to move from research prototype toward practical engineering training tools. Engineers who continuously develop these abilities will be better prepared for rapidly changing industrial environments.

Looking Beyond Today's Technology

Although several technical and organizational challenges still remain, the long-term outlook for Virtual Reality in mechanical engineering is highly promising. As hardware becomes more affordable, software continues to improve, and AI technologies mature, VR is expected to become an integral part of engineering practice. Ultimately, future mechanical engineers will not only design physical products but also create intelligent, connected, and sustainable systems that seamlessly combine the physical and virtual worlds.

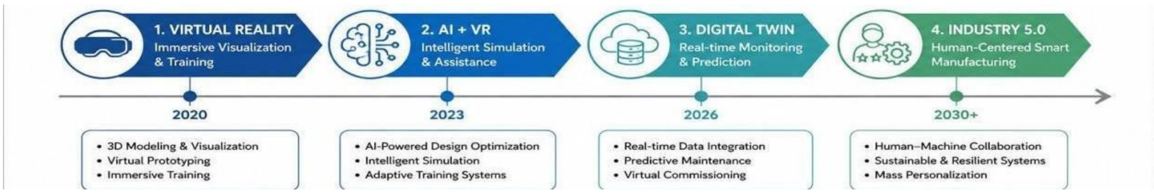

Figure 5. Roadmap for the evolution of VR technologies towards Industry 5.0 in mechanical engineering.

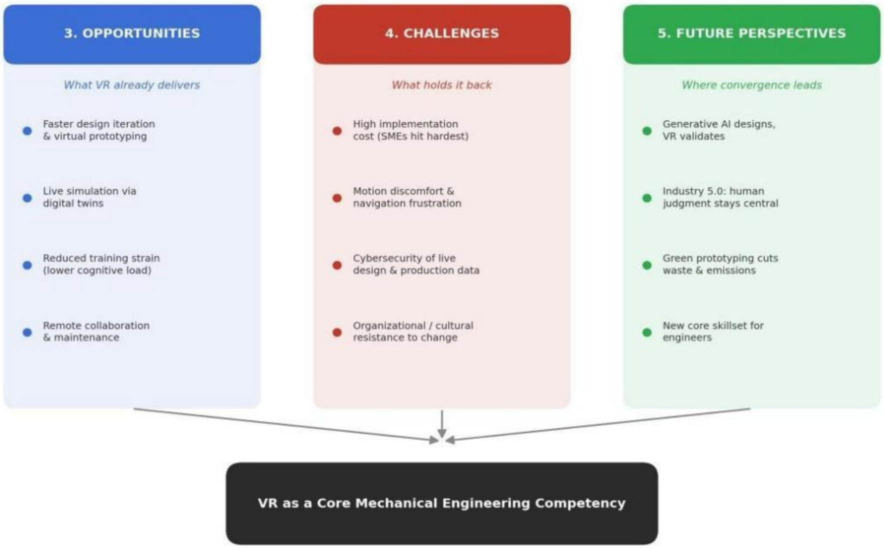

Figure 6. Convergence of opportunities, challenges, and future perspectives toward VR as a core mechanical engineering competency.

Conclusion

Virtual Reality (VR) is transforming mechanical engineering from a visualization technology into a core engineering tool that enhances product design, simulation, manufacturing, maintenance, collaboration, and engineering education while improving design accuracy, reducing development time and costs, and supporting safer, more efficient workflows. Its integration with digital twins, artificial intelligence, and Industry 5.0 further strengthens intelligent decision-making, predictive maintenance, and human-centered manufacturing. However, widespread adoption remains constrained by high implementation costs, hardware and software limitations, cybersecurity concerns, motion discomfort, and shortages of professionals with interdisciplinary digital skills. This review, based on a narrative synthesis of representative literature, is limited by the absence of a systematic review or meta-analysis, highlighting the need for future empirical studies, cross-industry validation, economic evaluations, and standardized assessment frameworks for usability and long-term engineering performance. As immersive technologies continue to mature, mechanical engineers will increasingly require competencies in VR, AI, digital twins, data analytics, and smart manufacturing to design and optimize intelligent cyber-physical systems. Overall, VR is expected to become a fundamental component of next-generation mechanical engineering, enabling greater innovation, productivity, sustainability, and global competitiveness in the Industry 5.0 era.

Perhaps, in the coming decades, Virtual Reality will not only become a supportive tool for mechanical engineers but also a core element of engineering innovation, enabling new ways of designing, creating, and interacting with the physical world.

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