IMMERSIVE REALITIES WORKING GROUP

The Use of Virtual Reality Technologies in (Engineering) Education

Best Practice Sheet

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Introduction

Virtual Reality (VR) is often defined as "creating real-life experiences using computer graphics," and can take the form of both Immersive Virtual Reality (IVR) and non-immersive, Desktop Virtual Reality (DVR) (Bano et al., 2024, p. 2; Ghazali et al., 2024). VR operates under the broader umbrella of Extended Reality (XR) technologies, which also includes Augmented Reality (AR) and Mixed Reality (MR), and has seen rapid advancements in recent years. While "its appeal on gaming platforms is well-established, it is also gaining traction in the realm of education [and] training" (Ghazali et al., 2024, p. 1).

Particularly in fields requiring practical training involving complex, costly, or hazardous processes, the promise of leveraging VR technologies for education cannot be overstated. This is especially true for engineering, where immersive simulations of spatially and technologically intricate machinery, interactive manufacturing environments, and experiential learning practices can significantly bridge the gap between theory and application.

This best practice sheet offers an evidence-based, practical guide for designing VR-based learning environments in mechanical engineering education with a specific focus on Additive Manufacturing. Drawing on a wide range of academic literature, technical studies, and real-world use cases, it integrates key pedagogical principles, technical implementation strategies, and domain-specific insights to support instructors, curriculum designers, and VR developers.

The document is structured with a progressive focus:

- It begins by setting the theoretical foundations for the use of VR in education.
- It then turns to outlining general best practices for designing VR-based education across disciplines.
- It then focuses on why VR is considered to be especially useful for engineering education.
- Lastly, it culminates in illustrating engineering-specific real-world use cases of VR for education.

While the educational potential of VR has often been praised anecdotally, this document consolidates evaluated evidence, offering actionable recommendations on what works and what should be avoided. The overarching goal is to support the development of pedagogically meaningful, cost-effective, and technically feasible VR applications that enhance both learning outcomes and instructional efficiency.

1 Foundations: Virtual Reality and Learning Theories

VR has emerged as a powerful educational tool by enabling immersive, interactive learning environments that support a wide array of pedagogical frameworks. It is particularly well-aligned with contemporary theories of learning that emphasise experience, construction, and social interaction. As the integration of VR into educational practice grows, its theoretical underpinnings must be acknowledged to guide meaningful and evidence-based application.

One of the most prominent theoretical frameworks associated with VR is **Experiential Learning Theory (ELT).** Developed by Kolb (1984), ELT describes learning as a cyclical process of concrete experience, reflective observation, abstract conceptualisation, and active experimentation. VR has been shown to effectively support all four phases (Karadayı & Evin-Gencel, 2024). In the LADUVR[1] project, for instance, students engaged in architectural design by reflecting on and reworking their virtual models, illustrating experiential learning through immersive technology (Maghool et al., 2018). Research confirms that immersive environments promote deep conceptual understanding by connecting sensory engagement with abstract thought (Aiello et al., 2012; Bano et al., 2024; Marougkas et al., 2023).

VR also aligns closely with **Constructivist Learning Theory,** which asserts that learners actively construct knowledge through meaningful experiences. Scholars highlight how VR supports constructivism by creating problem-oriented environments where students interact with virtual objects and test hypotheses within contextually rich simulations (Aiello et al., 2012; Bashabsheh et al., 2019; Christou, 2010; Lai et al., 2020; Soliman et al., 2020). These environments promote inquiry, manipulation, and reflection -cornerstones of constructivist practice (Khukalenko et al., 2022; Radianti et al., 2020; Scavarelli et al., 2021).

In addition, **Social Learning Theory,** which focuses on observation, collaboration, and modelling, is increasingly applied in VR contexts. VR environments allow learners to engage with peers, receive real-time feedback, and co-construct knowledge in shared virtual spaces (Mallek et al., 2024; Pellas et al., 2020). These collaborative experiences are particularly impactful in fostering communication skills, critical thinking, and empathy in diverse learning groups (Hamilton et al., 2021; Khukalenko et al., 2022).

Beyond theoretical frameworks, recent studies emphasise **Cognitive Load Theory (CLT)** and the **Cognitive Theory of Multimedia Learning (CTML)** as essential for effective VR design. Oje et al. (2023) stress that VR learning environments (VRLEs) must minimise the extraneous

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cognitive load by avoiding irrelevant visual effects, ensuring meaningful pre-training and sequencing tasks to match learner capacity. CTML principles, such as the modality and coherence effects, have direct implications for VR design: well-structured VR scenarios can enhance comprehension by aligning spoken narration with visuals while removing distracting elements (Mayer, 2017; Moreno & Mayer, 2000). Equally important is VR's capacity to support kinesthetic and procedural learning. By engaging learners in physical interactions with digital content, VR facilitates "learning-by-doing," enabling skills practice in safe, repeatable environments (Scrivner et al., 2019). This is especially valuable in disciplines like engineering, where learners benefit from the virtual manipulation of complex machinery and design components (Ghazali et al., 2024; Radianti et al., 2020).

Finally, VR has been shown to increase motivation, emotional engagement, and knowledge retention, especially when combined with clear instructional goals and reflection opportunities (Hamilton et al., 2021; Klingenberg et al., 2022; Nicolaidou et al., 2023). Its potential is especially significant when integrated thoughtfully into blended learning scenarios or scaffolded instructional sequences.

In sum, the theoretical foundations for VR in education are robust and multidimensional. By incorporating insights from constructivism, experiential and social learning theories, cognitive load management, and motivational design, VR can serve as a deeply engaging and effective instructional tool. However, as multiple studies caution, its success depends on the intentional, theory-informed design that goes beyond technological novelty to prioritise pedagogical impact.

2 VR for Education: General Best Practices

Leveraging Virtual Reality (VR) technology for educational purposes presents a unique opportunity to enhance the bridging of theory and praxis and move beyond traditional instructional paradigms. While there are nuances and particularities depending on the topic and field of education, there is a range of general best practices that the literature and prior experiences present. This section will provide an overview of these general best practices that are applicable across domains and hence form the foundation of VR education best practices.

Purpose & Pedagogical Fit

The first major aspect that becomes apparent across the literature **is the importance of not losing track of purpose and intent** when implementing VR in education. While technological developments undoubtedly present new and exciting opportunities, it is imperative not to let these possibilities dictate or shift the intended educational goals. Instead, VR should be approached with clear pedagogical objectives. Rather than being guided by technological novelty, effective VR learning environments should be built around defined learning outcomes and be closely aligned with curricular goals. This also means that when it is not apparent how VR adds value to a given process or outperforms other ways of reaching a desired outcome, there is no reason to force its use for the sake of innovation alone. Instead, VR should be "designed for learning" and integrated purposefully, supporting learning processes where it can be meaningfully linked to intended pedagogical outcomes (Fowler, 2015; Fromm et al., 2021; Ghazali et al., 2024; Karadayı & Gencel, 2024; Oje et al., 2023; Radianti et al., 2020).

Curriculum Integration & Learning Theories

This emphasis on pedagogical alignment is consistently reflected in the literature. Karadayı and Gencel (2024) underscore the importance of curriculum integration in their case study on teacher education, arguing that VR should be carefully embedded into broader course structures and linked to experiential learning frameworks, such as Kolb's cycle. Fromm et al. (2021) echo this view by emphasising the importance of designing with purpose and, rather than asking ***"What can we do with this emerging technology?"***, state the importance of asking ***"What kind of learning outcome should be achieved and what is the most***

effective learning process to achieve this outcome?". In their systematic review, Radianti et al. (2020) provide further support for this perspective. They conclude that the success of VR in education depends on how well it is aligned with instructional design, and point out that many implementations fail to link immersive experiences to a coherent pedagogical framework and established learning theories.

The direct link and **grounding of VR design in established learning theories** that were touched upon above, particularly constructivist and experiential learning paradigms, is the next consistently present best practice. This is not merely a theoretical preference, but a practical best practice because these frameworks provide clear, research-backed guidance for structuring learner interaction, engagement, and reflection in virtual environments. Constructivist theory, which emphasises that learners build knowledge through active exploration, problem-solving, and interaction, aligns naturally with VR's interactive and immersive capabilities. Designing VR experiences according to this theory means giving learners agency -allowing them to manipulate virtual environments, explore scenarios, test hypotheses at their own pace, and engage with challenges that require critical thinking and decision-making (Christou, 2010; Khukalenko et al., 2022; Rouhani et al., 2024; Scavarelli et al., 2020). For instance, instead of simply presenting a pre-scripted demonstration, a constructivist VR environment might ask students to solve a problem, navigate a simulation, or make choices that affect outcomes, turning the learner into an active participant rather than a passive observer (Christou, 2010; Khukalenko et al., 2022; Scavarelli et al., 2020). Experiential learning theory, particularly Kolb's four-stage learning cycle (concrete experience, reflective observation, abstract conceptualisation, active experimentation), further strengthens this practice by offering a structured model for learning design (Bano et al., 2024; Fromm et al., 2021).

VR Sequence Design

This **reflection on where to place the VR experience within the larger educational and instructional design and sequencing** is another important best practice that emerges from the literature. While VR can offer groundbreaking possibilities for learning through immersion, real-world simulations, etc., effective VR-based education is rarely standalone. Instead, it must be tightly embedded into broader instructional sequences that include careful preparatory steps and in-depth follow-up. This ties back to the learning theories and shows why grounding VR design in theory implies that a simulation is not an isolated experience, but part of a broader instructional sequence that includes preparatory activities, in-VR experience, and post-activity reflection (Fromm et al., 2021; Klingenberg et al., 2022; Oje et al., 2023). Oje et al. (2023) and Klingenberg et al. (2022) show that when people are given time to reflect on their virtual actions, draw conclusions, and then reapply knowledge in new contexts, learning becomes significantly deeper and more durable. Preparation, not just organisational but also pedagogical, is crucial for the VR experience to take place safely and for it to foster learning. The same holds for post-VR processes like active reflection, discussions, and feedback. Thus, theory-informed design and a purpose-driven curation of learning processes that integrate VR as a step in the process rather than a standalone activity can provide scaffolding and create learning pathways that support knowledge construction, retention, and transfer.

User-Centred & Accessible Design

Another generally applicable best practice is that **VR design should be user-centred and accessible.** There are several studies that emphasise the need for ergonomic considerations, intuitive interfaces, and affordable hardware to reduce exclusion and increase scalability (Bell & Fogler, 1997; Cook et al., 2019; Lai et al., 2020; Radianti et al., 2020; Soliman et al., 2021). Usability is a critical component of effective VR-based education, not only in terms of comfort and immersion but also for managing cognitive load and preventing user frustration. There are numerous sources that stress the importance of minimising system complexity to ensure intuitive, consistent navigation and interaction (Lege & Bonner, 2020; Oje et al., 2023).

In terms of the sophistication level of immersion, literature proposes a careful balancing act. On the one hand, features like 3D depth, realistic motion, and multisensory interaction can significantly enhance learner engagement and the feeling of "being there" while their lack, or visual aberrations and low-quality 3D experiences can lead to immersion- and illusion-breaking and have negative effects (Di Lanzo et al., 2020; Kavanagh et al., 2017; Lege & Bonner, 2020). Kavanagh et al. (2017) observed that insufficiently realistic or inconsistent environments can detract from the learning experience, as they disrupt the sense of presence and immersion. However, on the other hand, excessive complexity, unnecessary details, or overstimulation can lead to cognitive overload, distractions, or even simulator/motion sickness and ultimately undermine learning outcomes (Oje et al., 2023; Radianti et al., 2020; Soliman et al., 2021). There is ample evidence of overly complex and hyper-realistic VR environments actually impeding learning outcomes by distracting the users from the task at hand (Alves Fernandes et al., 2016; Soliman et al., 2021; Southgate et al., 2019; Zinchenko et al., 2020). A study by Petersen et al. (2022) observed that students who learned in highly aesthetic VR environments performed worse than those who learned in more simplistic VR environments with less aesthetic detail.

Hence, this tension calls for **deliberate design choices that optimise immersion while minimising potentially distracting features** by ensuring visual consistency, reducing excessive stimuli, and maintaining coherence in the sensory design, elements that support rather than interfere with cognitive processing. In line with "designing for learning", pedagogical outcomes and merit must be prioritised over aesthetics and immersive sophistication.

Health, Safety & Cybersickness Mitigation

This goes hand in hand with the next general best practice for VR in education: **Health, safety, and well-being of learners**. Although it was already touched upon briefly, risks such as motion sickness, eye strain, or cognitive overload are key challenges to the successful integration of VR into education. A recurring issue across the literature is VR-induced motion sickness, or precisely simulator sickness, with symptoms such as nausea, disorientation, and fatigue, typically caused by mismatches between visual input and vestibular perception (Christou,

2010; Cook et al., 2019; Ghazali et al., 2024). Interestingly, and in line with the call to limit overcomplexity, Christou (2010) observes that the more realistic a simulation is, the higher the risk of triggering adverse reactions, as stronger sensory cues more intensely stimulate vestibular reflexes.

Hence, this concern is particularly relevant for more sophisticated simulations, which, while visually impressive, may exceed users' sensory thresholds. Nevertheless, Akbulut et al. (2018) similarly observed instances of motion sickness among students using low-cost headsets like Google Cardboard in educational settings, underscoring the need to offer alternative formats like 2D versions for more sensitive users. Key factors that can lead to disorientation and simulator sickness are issues like graphical rendering delays, interface complexity, and the absence of spatial reference cues (e.g., horizon lines) (Cook et al., 2019). Some practical measures that are suggested in the literature include the introduction of visual anchors (like horizon lines) within the VR environment, using high frame rates (higher than 90/120 FPS) and reducing latency, as well as physical remedies like offering ginger candy, and time limitations per headset session (Cook et al., 2019; Elbamby et al., 2018; Elia et al., 2019; Rouhani et al., 2024; Wang et al., 2023). A frequently suggested mitigation technique is to *add visual cues and reminders* that allow a user to see representations of him/herself in the immersive environment. This can be achieved by adding virtual noses or personal mirrors (Cook et al., 2019; Rouhani et al., 2024; Wienrich et al., 2018).

Furthermore, research suggests that *narrowing the field of view* (FOV) can be an effective strategy for mitigating motion sickness in VR environments. Empirical studies have demonstrated a negative correlation between FOV size and the severity of VR sickness symptoms, indicating that a reduced FOV generally leads to lower sickness scores (Rouhani et al., 2024). However, this mitigation strategy comes with trade-offs. While narrowing the FOV can enhance user comfort, it may simultaneously diminish the sense of presence and overall enjoyment within the virtual environment, again hinting at the delicate balancing act of creating an enjoyable and realistic immersion while reducing unnecessary and overly complex elements (Lin et al., 2002; Rouhani et al., 2024; Seay et al., 2001). Ghazali et al. (2024) reinforce this position by identifying cybersickness, a type of motion-induced discomfort specific to immersive media, as one of the most notable challenges in VR education. The literature emphasises **limiting the duration of exposure ideally to less than 15 - 20 minutes**, breaking VR sessions into manageable segments, carefully selecting HMDs based not only on financial constraints but also on their cybersickness profile (Garrido et al., 2022; Ghazali et al., 2024; Hendrika et al., 2020; Hurter et al., 2021; Rebenitsch & Owen, 2021). Hendrika et al. (2020) and Rouhani et al. (2024) support that segmenting VR use into shorter, task-focused intervals interspersed with reflection helps limit discomfort and enhances knowledge consolidation. They also add that *giving users active control over movement* in VR, as opposed to passive movement, can be an effective countermeasure to simulator sickness.

Across these studies, there is a strong consensus that **health and safety are not optional considerations, but foundational aspects of educational VR design that directly affect learning outcomes**. When students experience physical discomfort or distraction due to headset design, environmental quality, or interface logic, the intended benefits of immersion are rapidly

lost. Therefore, designing for physical well-being, emotional comfort, and accessibility must be understood as integral to pedagogical success. Rather than being treated as secondary to learning goals, these elements form the conditions under which deep, equitable, and sustained engagement with VR can take place (Akbulut et al., 2018; Christou, 2010; Cook et al., 2019; Ghazali et al., 2024; Oje et al., 2023; Radianti et al., 2020).

Social Presence & Collaborative Learning

Another best practice is the importance of **social presence and collaborative learning** in VR environments. VR is not only a medium for individual interaction but can also support shared tasks, multi-user engagement, and peer learning processes. Several studies stress that collaborative VR tasks, when structured around meaningful objectives, foster critical thinking, empathy, and motivation (Cibulka & Giannoumis, 2017; Kumar et al., 2021; Oje et al., 2023). Activities such as co-navigation, real-time problem-solving, and shared simulations promote social learning and mirror real-world teamwork, which is especially valuable in professional and technical training contexts (Fromm et al., 2021; Scavarelli et al., 2020). To be effective, however, collaboration must be intentionally designed into the experience through shared challenges, guided reflection, or cooperative role distribution rather than relying on incidental interaction alone (Fromm et al., 2021; Radianti et al., 2020).

Additional Considerations

In addition to pedagogical and design-oriented principles, the successful implementation of VR in education also depends on **adequate support infrastructure**. This includes training educators in the effective use of VR tools, ensuring technical support for setup and troubleshooting, and preparing learning environments to accommodate VR activities (Bell & Fogler, 1997; Radianti et al., 2020). Without proper training, even well-designed systems can fail to deliver their intended benefits. Furthermore, **considerations of data protection and privacy**, particularly relevant in educational contexts involving minors or sensitive biometric data, must be accounted for when selecting VR platforms and applications. Designers and institutions should adhere to local data protection laws (e.g., GDPR[2]), avoid unnecessary tracking, and ensure transparent consent processes when collecting any learner data.

Taken together, these general best practices, ranging from pedagogical alignment and theory-grounded design to usability, collaboration, support systems, and learner well-being, form the foundation of effective VR-enhanced education. In the following section, these principles will be further specified and applied to the context of engineering education, where the unique affordances of VR can be harnessed to support the acquisition of spatial, procedural, and technical knowledge in immersive, interactive environments.

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At a Glance: General VR in Education Best Practices

Goal-first design

Define measurable learning outcomes -> only use VR where it clearly adds value.

Curricular alignment

Embed VR in course objectives and assessments, ground in constructivist & experiential theories (e.g., Kolb).

Sequenced learning

Ensure proper preparation before- and implementation and reflection after- VR Implementation.

Usability & access

Minimise cognitive load, keep navigation consistent, prefer “clear & simple” over hyper-realistic visuals.

Health & safety

Limit sessions (≤15–20 min), ensure high FPS/low latency, provide visual anchors & optional 2D modes, allow user-controlled movement.

Collaboration by design

Build shared tasks/roles and guided reflection to leverage social presence and teamwork skills.

Support, Infrastructure & governance

Train instructors, provide tech support, consider questions of privacy, data protection and consent.

3 The Case of VR for Engineering Education

Before moving to the specific use cases for using VR in engineering education and Additive Manufacturing (AM), a few remarks on the promise that VR technologies hold for this sector in particular. It is important to state that the best practices that specifically apply to engineering education are very limited, as the best practices discussed in the general section translate and apply to engineering as well, and already constitute the most important best practices.

Engineering disciplines regularly involve tasks that are procedural, spatial, costly, and hazardous, often making training and practice very difficult. Learning how to handle heavy machinery or rehearsing repetitive assembly tasks, for example, can prove difficult in spatially complex and dangerous contexts or using expensive resources.

VR is especially promising because of its ability to simulate these complex and large physical environments and objects, visualise abstract or spatially intricate concepts, and enable repeated, hands-on practice in a safe and cost-effective manner (Akbulut et al., 2018; Bano et al., 2024; Beck, 2019; Bell & Fogler, 1997; Christou, 2010; Cook et al., 2019; Di Lanzo et al., 2020; Ghazali et al., 2024; Jensen & Konradsen, 2018; Kumar et al., 2021; Oje et al., 2023; Soliman et al., 2021; Wang et al., 2018).

Beyond dangerous, costly, or spatially intricate concepts, VR can also aid learning and understanding of concepts that can not be physically observed, like electromagnetism or three-dimensional (3D) statics. Here, students can interact with 3D magnetic fields, testing different configurations and observing the results firsthand (Di Lanzo et al., 2020; Manseur, 2005). This hands-on experience, in turn, is directly aligned with what constructivist and experiential learning theories suggest for better learning and retention (Bano et al., 2024; Christou, 2010; Fromm et al., 2021; Lege & Bonner, 2020; Oje et al., 2023; Radianti et al., 2020; Soliman et al., 2021). Indeed, the ability to visualise internal systems and test designs in simulated environments allows students to link theory and practice more effectively by observing cause-and-effect relationships in real time. By adjusting settings and seeing the immediate outcomes, students reinforce their problem-solving skills and deepen their understanding of engineering systems (Bano et al., 2024; Cibulka & Giannoumis, 2017; Fromm et al., 2021; Han, 2023; Kumar et al., 2021).

Empirical research strongly supports the effectiveness of VR-based learning in engineering education. Controlled studies consistently show that students engaging with VR environments outperform their peers in knowledge retention, conceptual comprehension, and applied performance tasks (Akbulut et al., 2018; Di Lanzo et al., 2020; Kumar et al., 2021; Salah et al.,

2019). For instance, Akbulut et al. (2018) found that computer engineering bachelor students using the so-called "Virtual Reality Enhanced Interactive Teaching Environment" (VR-ENIT) achieved 12% higher assessment scores compared to those taught through conventional instruction. Comparable improvements have been documented in Salah et al. (2019), where students learning via immersive VR simulations were significantly faster and more accurate than the control group in completing tasks about reconfigurable manufacturing systems (RMS).

Beyond Learning: Sustainability, Cost, Scale & Access

There are several key advantages of the use of VR in engineering education beyond the learning outcome of the students that deserve to be mentioned. Specifically, **VR technologies can offer solutions to challenges such as sustainability, cost-effectiveness, scalability, and adaptability,** which are critical in today's fast-evolving academic environments (Di Lanzo et al., 2020; Ghazali et al., 2024; Kumar et al., 2021; Oje et al., 2023; Soliman et al., 2021). One of the most compelling reasons for adopting VR in engineering education is its potential to enhance sustainability in both the teaching practices as well as the sector as a whole. Traditional engineering courses often rely on physical resources, from prototype materials and lab equipment to consumables, all of which not only cost a lot but also generate environmental waste.

VR could offer a more sustainable and resource-saving alternative by enabling digital simulation of processes, systems, and environments, thereby reducing material waste and the environmental footprint of engineering instruction (Cibulka & Giannoumis, 2017; Han, 2023; Soliman et al., 2021; Wang et al., 2018). Particularly in areas where design iteration is frequent and material usage is high, VR enables students to refine concepts without consuming raw materials and to explore these technologies in a safe environment.

However, this potential benefit of using VR must be carefully contrasted and balanced with the material and environmental costs of developing, implementing, and maintaining the VR technologies. Importantly, next to these material considerations, VR is increasingly recognised as a medium for advancing sustainability education in engineering. By allowing students to simulate resource-efficient designs, assess energy consumption, and visualise the environmental impact of their decisions, VR provides a dynamic environment for experiential learning about sustainable engineering practices (Bano et al., 2024; Salah et al., 2019; Soliman et al., 2021). Hence, VR can not only promote more sustainable education practices but also foster the development of environmentally conscious decision-making among students (Bano et al., 2024; Soliman et al., 2021). Directly related to the issue of sustainability, VR also addresses the prohibitive costs often associated with traditional engineering instruction. Lab construction, machinery procurement, resource consumption, and operational maintenance require major investments, which VR technologies could partially offset. Students can safely repeat experiments as often as necessary without incurring additional material costs (apart

from the operational costs) or safety concerns (Cibulka & Giannoumis, 2017; Ghazali et al., 2024; Kumar et al., 2021; Wang et al., 2018).

Cost efficiency is matched by scalability. Especially in institutions facing growing enrollment, this makes VR a highly attractive alternative to building additional lab facilities (Kumar et al., 2021; Soliman et al., 2021). Furthermore, during periods of disruption, such as the COVID-19 pandemic, VR has proven to be a critical enabler of instructional continuity (Kumar et al., 2021; Soliman et al., 2021). For instance, Seifan et al. (2019) showed how VR was used for virtual field trips for undergraduate students in an engineering biotechnology course at the University of Waikato. The promises for remote learning using VR also extend to considerations of equity and accessibility. Students in remote regions, with physical disabilities, or lacking access to well-equipped labs can now engage in interactive engineering simulations through widely available headsets or desktop setups (Cibulka & Giannoumis, 2017; Ghazali et al., 2024; Halabi, 2019).

Taken together, it becomes apparent why engineering education is a sector in which the use of VR can be especially promising. Its ability to **safely simulate high-risk or cost-intensive processes, make invisible phenomena tangible, and support sustainable, scalable, and inclusive instruction** has made it a focal point of innovation across technical education landscapes. As the next subsection will demonstrate, these conceptual advantages are not merely theoretical; they are increasingly reflected in a wide array of real-world implementations, pilot projects, and evaluated case studies across engineering domains, including, most notably, in the field of AM.

Exemplary Use Cases & Best Practices of VR in Engineering Education

As outlined in the previous sections, the potential of VR in engineering education is closely tied to its ability to align with experiential and constructivist learning theories, support sustainable and cost-efficient instruction, and enable scalable, collaborative, and safe learning environments. These conceptual advantages are not just theoretical but are increasingly being realised through a growing number of real-world use cases, projects, structured course integrations, and institution-wide implementations. This section offers an overview of real-world examples that illustrate the effective and diverse uses of VR in engineering education. They serve not only as validation of prior claims but as concrete, inspirational references for future curriculum design and VR development.

Industrial & Process Simulations

As established above, a key strength of VR for engineering education lies in its capacity to simulate complex, industrial-scale processes without the associated risks or costs. A strong example of theory-informed process training is the ViRILE[3] simulator, developed for chemical engineering students to engage with the operation of a polymerisation plant in a safe, immersive environment (Kumar et al., 2021; Schofield, 2012). Two other examples further illustrate VR's capacity to simulate complex industrial systems and processes using two immersive crude distillation units (CDUs). Norton et al. (2008) identified that engineering students in chemical, process, and related disciplines were lacking industry exposure and practical experiences due to factors like costs, litigation concerns, as well as logistical constraints. Using spherical industrial imagery from BP's Bulwer Island Refinery coupled with interactive activities and content, they developed a theory-driven (i.e., constructivism & cognitive load theory) VR environment for university students and industrial staff (Norton et al., 2008). Similarly, Pirola et al. (2020) developed a virtual CDU environment with immersive tours and time-bound exercises for undergraduate students. Their evaluation showed that students' test scores on CDU theory doubled after engaging with the VR module, accompanied by strong positive feedback on its pedagogical effectiveness.

In a different setting, at the department of chemical and process engineering of the University of Canterbury, Herritsch et al. (2011) recognised that student field trips were becoming increasingly difficult to organise due to time constraints and safety concerns. As a remedy, they created a desktop-based virtual environment simulating a skim milk powder processing facility. They integrated 360-degree panoramic views, spherical photography, process flow diagrams (PFD), piping and instrumentation diagrams, 3D drawings, and supplementary material (e.g., text, videos, simulation programs, and images) into a virtual walkthrough.

Built using Adobe Flash Builder, it prioritised usability and was specifically tailored for undergraduate engineering students. An evaluation of the interface by Abdul Rahim et al. (2012) confirmed that students found the interface intuitive and engaging, supporting both spatial orientation and conceptual understanding of complex process systems. Such applications are powerful illustrations of how VR can address the high material, spatial, and safety constraints associated with real-world engineering environments, as previously discussed. They also mirror the importance that is placed on visualising concepts and experiencing hands-on learning, which is apparent in both constructivist and experiential learning theories.

From Abstract Phenomena to AM Workflows

Merlin's Playground is an example of visualising phenomena that are not physically observable. Developed at Multimedia University in Malaysia, part of the Merlin project was an interactive virtual lab that was designed to support the teaching of electromagnetism, an area

3 (Virtual Reality Interactive Learning Environment)

typically difficult for students to grasp due to its intangible nature. Ghazali et al. (2024) found that students who engaged with Merlin's Playground demonstrated a substantial improvement in their understanding of magnetostatics, as evidenced by a rise in average assessment scores from 67.95% before the VR session to 83.03% afterwards. The results suggest that the experience in the immersive environment significantly helped the students grasp abstract electromagnetic concepts.

A particularly well-structured implementation of VR in Additive Manufacturing education is presented by Rafa et al. (2024), who developed a fully immersive training environment simulating a Selective Laser Sintering (SLS) lab. Built in Unity and making use of HTC Vive Pro Eye headsets, the system simulates the workflow of a real-world industrial lab, guiding students through each step of the AM process from protective equipment preparation and print parameter setup to machine operation and post-processing. To approximate real-world problems, they created the cost-constrained task of producing a shoe insole under $ 8. The simulation required learners to engage in technical decision-making while balancing economic and operational trade-offs. The design is closely aligned with experiential learning principles, emphasising active engagement, repeated practice, and interaction with realistic constraints. The evaluation combined both objective and subjective methods. Eye-tracking data revealed that students concentrated most intensely on the control station, indicating the cognitive demands of cost-sensitive planning. Learning outcomes improved notably in post-training assessments, particularly in material selection and risk estimation, although a slight drop in certain conceptual questions suggested possible cognitive overload. Usability ratings were high, and simulation sickness remained minimal. Nonetheless, the study pointed to important areas for refinement, such as incorporating auditory cues, real-time feedback, and a more cognitively supportive interface layout.

These insights resonate with earlier findings from Penn State and Carnegie Mellon, where Ostrander et al. (2020) compared interactive and passive VR instruction for introductory AM training. Their results showed that both approaches achieved learning outcomes comparable with traditional settings, while interactive VR further improved students' self-efficacy, reinforcing the importance of agency and guided experimentation. Taken together, both studies substantiate key claims made throughout this document: that VR, when deliberately designed and pedagogically grounded, not only reproduces the value of physical labs but enhances it by fostering deeper engagement, accessible scalability, and meaningful decision-making practice in complex engineering contexts.

Cross-Domain & Systems-Level Implementations

Building on these findings, further examples from other subfields of engineering education continue to illustrate how VR can support domain-specific skill acquisition, procedural learning, and conceptual clarity through immersive, practice-oriented environments. For example, Zhang et al. (2018) demonstrate how VR environments can immerse learners in weft-

knitting machinery operation, enhancing their operational skills, practice ability, and overall understanding of textile engineering systems. Similarly, Ouyang et al. (2018) highlight the benefits of VR in simulating chemical production plant operations, while Barata et al. (2015) use VR to train engineering students to operate transformers in electrical power stations. Furthermore, civil and construction engineering, with their inherently high spatial and temporal complexity, have also particularly benefited from VR's immersive capabilities. The Interactive Building Anatomy Model (IBAM), draws on the concept of medical anatomy models and enables students to interactively explore building components by detaching, attaching, and dissecting them within a virtual environment (Park et a., 2016; Wang et al., 2018). Interim findings suggest that the system provides a sufficient level of interactivity to support learner engagement and understanding, offering a promising approach to enhance student competence in a field where traditional methods often fall short.

A more advanced implementation of VR in construction engineering education involves Building Information Modelling (BIM)-enabled VR systems that allow students to inspect architectural and engineering systems in real-time, recognise design problems, and understand layered dependencies across disciplines (Russell et al., 2013; Wang et al., 2018; Xie et al., 2011). As Wang et al. (2018) show, BIM-based VR has become the most widely adopted immersive technology in construction engineering education, particularly for architecture visualisation, construction sequencing, and structural systems understanding. Unlike traditional CAD (Computer-Aided Design) or desktop-based VR systems, these environments provide real-time updates and retain the full metadata of the building elements, allowing learners to experience and assess the implications of their design choices dynamically. Through tools like Autodesk Revit Live, students can move fluidly from 2D schematics into spatially immersive environments while maintaining access to structural, material, and cost-related parameters (Wang et al., 2018). The review also highlights that such applications significantly enhance learner engagement and spatial reasoning. Likewise, Salah et al. (2019) demonstrate how the Virtual Learning Factory (VLF) for Reconfigurable Manufacturing Systems (RMS) can effectively support training in modularity and system adaptability. In a course at King Saud University, students used a semi-immersive VR platform to design and optimise layouts for a machine vice production line. Compared to peers using traditional methods, VR-trained students completed tasks faster, made fewer errors, and reported greater satisfaction, highlighting VR's value for complex, experiential learning. In line with prior sections (best practices) of this paper, Wang et al. (2018) note potential drawbacks such as usability challenges with HMDs and the need for curricular frameworks that can guide the pedagogical integration of these technologies.

A further interesting use case is the Operator Training Simulator (OTS) by Manca et al. (2013). This VR environment is used in chemical process engineering to train operators to handle high-risk and accident scenarios that cannot be safely replicated in real-world settings. The OTS combines dynamic process simulation with accident simulation to prepare field operators for both routine tasks and critical incidents. A case study involving a simulated hydrodealkylation (HDA) plant accident allowed trainees to experience and respond to a virtual toluene leak, improving their situational awareness, decision-making, and cognitive readiness (Manca et al., 2013). The system enables operators to "experience" the plant and its units, comprehend their meaning and purpose, and learn how to project the status quo into the future, addressing

all three components of situation awareness. By integrating these elements in a realistic and risk-free environment, the tool fosters cognitive resilience and enhances safety preparedness in ways traditional training cannot. This example clearly aligns with earlier discussions on the benefits of experiential learning and the role of VR in procedural education and safety-critical skill development.

At the systems level, one of the most established and widely cited examples is the Technology-Enabled Active Learning (TEAL) classroom at MIT (Massachusetts Institute of Technology). The teaching format initially designed to counteract the passivity of traditional lectures, TEAL combines immersive simulations, collaborative labs, and inquiry-driven pedagogy to encourage active student engagement and conceptual understanding (Cibulka & Giannoumis, 2017; Dori & Belcher, 2005; Soliman et al., 2021). TEAL and similar environments use visualisations and hands-on tasks to scaffold knowledge acquisition and improve knowledge retention, particularly in abstract STEM fields. The framework has proven especially effective in enabling a shift from passive to active and constructivist learning, boosting performance and motivation (Cibulka & Giannoumis, 2017; Seethamraju & Murthy, 2023; Soliman et al., 2021).

Taken together, these examples highlight not only the growing maturity and diversity of VR applications in engineering education but also their alignment with sound pedagogical principles. They illustrate how immersive technologies can be adapted to a wide range of instructional goals, from safety and hazard testing to virtual tours, and how they can be scaled across technical disciplines and institutional contexts. As such, **these cases provide robust, field-tested templates for anyone seeking to design meaningful, future-proof, and sustainable VR-based learning environments in engineering education.**

CONCLUSION

This best practice sheet set out to explore the potential of Virtual Reality (VR) as a transformative tool for engineering education, one that not only complements traditional instruction but meaningfully enhances it when designed and integrated with pedagogical intent. Drawing on a wide range of theoretical frameworks, empirical studies, and real-world implementations, the analysis has demonstrated that VR's value lies not in novelty but in its capacity to enable active, experiential, and context-rich learning in ways that are often unfeasible in physical settings.

As shown across the examples, VR excels in simulating hazardous, complex, or costly environments, allowing learners to practice technical skills, manipulate variables, and engage in repeated trial-and-error without material waste or safety risk. When aligned with frameworks like experiential learning theory, constructivism, and cognitive load theory, these environments do more than replicate reality; they scaffold understanding, foster problem-solving, and support the development of transferable, future-oriented competencies.

At the same time, the paper has emphasised that successful implementation requires careful design choices: pedagogical integration, accessibility, health considerations, and the minimisation of cognitive overload. These principles hold across domains but are particularly salient in engineering education, where spatial reasoning, procedural practice, and system-level thinking are central.

The wide range of use cases reviewed, from operator training systems and AM simulations to collaborative design platforms, demonstrates the maturity and versatility of VR as a learning tool. Collectively, they serve as an inspirational blueprint for institutions and educators aiming to build sustainable, inclusive, and scalable VR-based learning environments. While challenges remain, the evidence is clear: when approached with purpose and supported by sound instructional design, VR has the potential to reshape engineering education and set new standards for how knowledge is constructed, practised, and retained.

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A Best Practice Guide by the Immersive Realities Working Group at the TUM Think Tank

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