A VR lesson architecture for environmental engineering: Five scenario designs

Petru Iulian GRIGORE[1], Corneliu Octavian TURCU[1], Andrei ZAHARIA[2], Valentin NEDEFF[2]

[1] "Stefan cel Mare" University of Suceava, Faculty of Electrical Engineering and Computer Science, Suceava, Romania
[2] "Vasile Alecsandri" University of Bacau, Faculty of Engineering, Bacau, Romania

petru.grigore@student.usv.ro, cturcu@usm.ro, andrei.zaharia@ub.ro, vnedeff@ub.ro

Abstract: *Virtual reality is increasingly used in engineering education, yet many implementations provide limited detail on lesson structure and scenario specification, which constrains reuse across courses and institutions. This paper reports the design and implementation of a VR software package for Environmental Engineering organized as five scenarios covering wastewater sampling methods (introduced in a DAF-related context), a poultry slaughterhouse wastewater treatment process modeled with membrane bioreactor technology, and three immersive virtual laboratory modules addressing ultrafiltration, reverse osmosis, and UV disinfection. The contribution is a reusable lesson architecture that separates a conceptual micro-lesson layer from a practice-oriented workflow when applicable. In the theory-only scenarios, learners navigate structured explanations and decision prompts intended to support procedural reasoning. In the virtual laboratory scenarios, the lesson structure extends to guided assembly of an experimental stand, controlled process simulation, and measurement capture, followed by a debrief designed to connect parameter choices with observed system behavior. Scenario descriptions are presented using a consistent specification template (objectives, task sequence, interactions, outputs, and debrief prompts) intended to support extension to additional unit operations. A preliminary mixed-method teacher evaluation (N = 10) is also reported, indicating high perceived clarity of structure and teaching readiness. Future work targets learner-based feasibility measures (e.g., time-on-task and completion rates) and subsequent controlled studies using objective performance outcomes.*

Keywords: Virtual reality, Environmental Engineering, Ultrafiltration, Reverse Osmosis, Membrane bioreactor.

1. Introduction

Environmental Engineering education requires learners to reason about and operate multi-stage systems, including wastewater monitoring, membrane-based separations, and final disinfection. In many curricula, these topics are introduced mainly through lectures, schematics, and simplified examples, while access to handson laboratory practice is often limited by equipment availability, safety constraints, time, and cost. As a result, students may understand what a unit operation is intended to achieve, yet still lack procedural competence-how a system is assembled, started, monitored, and interpreted in a realistic workflow.

Virtual reality (VR) can address this gap by enabling immersive visualization and repeatable procedural rehearsal in a controlled environment. Although VR has been widely explored in engineering education, many reported implementations describe learning activities only at a high level, making it difficult to replicate or adapt lesson flow, scaffolding strategies, and scenario structures across different courses and unit operations. For Environmental Engineering-where instruction spans diverse processes and practical workflows-explicit (Zaharia et al., 2024a; Zaharia et al., 2024b), reusable lesson architecture is particularly important for instructional reuse and for preparing rigorous evaluation.

This paper presents a VR software package for Environmental Engineering implemented in Unreal Engine with controller based interaction, organized into five scenarios: (S1) wastewater sampling methods and techniques introduced in a dissolved air flotation (DAF) context; (S2) a conceptual walkthrough of a poultry slaughterhouse wastewater treatment process using membrane bioreactor (MBR) technology; (S3) ultrafiltration (UF) for final treatment of industrial wastewater; (S4) reverse osmosis (RO) for wastewater filtration; and (S5) Ultraviolet (UV) disinfection for real wastewater. Two scenarios are theory-oriented (S1-S2), while three implement an immersive virtual laboratory workflow (S3-S5) that includes guided assembly of an experimental stand, process simulation, and measurement capture.

The main contribution is a reusable VR lesson architecture that standardizes lesson phases (pre-brief, theory, assembly, simulation/measurements, debrief) while allowing learners to start from a selected phase based on instructional needs. The system integrates progressive hinting and checkpoint gating to support completion within classroom time constraints while preserving procedural validity. The package is already deployed in a laboratory context. Following the preliminary teacher evaluation reported in this paper, the next step is learner-based feasibility testing under authentic session constraints.

2. Background and design rationale

Virtual Reality and Virtual Laboratories (VLs) are increasingly used in engineering education to provide immersive, interactive environments that complement traditional instruction (Hamurcu, Timur & Rızvanoğlu, 2023). These platforms commonly support scenario-based learning by simulating real-world engineering problems (Grigore & Turcu, 2024; Grigore & Turcu, 2025) in a secure and cost-effective setting (Wang et al., 2022; Ciolacu et al., 2023). In Environmental Engineering, this approach is especially relevant because many topics are procedural and systems-based (e.g., wastewater treatment, membrane filtration, and disinfection), while access to physical laboratories is often constrained by infrastructure cost, time allocation, safety requirements, and space limitations (Coutinho, Magana & Dias, 2023).

VLs are frequently justified through several practical advantages over conventional laboratories. First, they can reduce the need for high upfront

equipment investment, ongoing maintenance, and specialized operational support, while enabling a one-time software implementation to be reused repeatedly (Vergara et al., 2022; Wang et al., 2022; Cook-Chennault & Farooq, 2023). Second, VLs mitigate risk by enabling practice in conditions that may be Dangerous, Impossible, Counterproductive, or Expensive (DICE) to replicate in real settings (Parlier, 2024; Grigore & Turcu, 2026), including failure modes and hazardous scenarios without personal injury or equipment damage (Jindal, Mittal & Bansal, 2023). Third, VLs improve accessibility by enabling learning independent of time and location, including exploration of remote or inaccessible environments that are difficult to visit physically (Jindal, Mittal & Bansal, 2023). Repetition without material consumption further supports practice until learners reach procedural fluency (Vergara et al., 2025). Additionally, VLs can enhance visualization of complex or hidden phenomena via information transparency and detailed observation mechanisms (e.g., zooming, slow motion, and seeing internal system parts) (Singh et al., 2021; Cook-Chennault & Farooq, 2023).

Building on this background, the proposed system (implemented in Unreal Engine) is designed around a clear separation between conceptual micro-lessons and virtual-lab workflows, enabling structured delivery while remaining flexible for classroom and laboratory use. The five-scenario suite applies consistent phases (pre-brief, theory, assembly, simulation/measurements, debrief) and allows users to choose the phase from which to begin, supporting targeted revision or focused procedural drills. To provide scaffolding without removing learner autonomy, the system integrates progressive hinting and checkpoint gating mechanisms. These features guide learners through complex tasks (e.g., UF/RO stand assembly and UV disinfection procedures) while managing cognitive load and ensuring prerequisite steps are satisfied before advancing. This paper reports the design and implementation of the package and presents a preliminary teacher evaluation; the next step is learner-based feasibility testing in the laboratory setting.

3. System and lesson structure

The VR application was developed in Unreal Engine and uses controller-based interaction for object manipulation and UI navigation. Content is organized as modular scenarios that share a common lesson framework, enabling a consistent user experience across different Environmental Engineering topics. A phase-selection mechanism allows learners or instructors to initiate a scenario from a chosen phase (e.g., theory-focused revision, assembly drill, or simulation run), supporting flexible classroom integration and reuse. The application was tested using a Meta Quest 3 head-mounted display, which served as the target hardware platform for interaction and usability evaluation. Each scenario follows a common phase model:

1. Pre-brief: objectives, learner role, expected outputs, and a short control reminder.
2. Conceptual micro-lesson (theory): concise explanation of the unit operation

purpose, main terms, and key cause-effect relationships.

3. Assembly/procedure: guided setup of an experimental stand, including verification steps.
4. Simulation and measurements: operation of the process in simulation and capture of required outputs/measurements.
5. Debrief: summary of what was done and reflection prompts linking actions and settings to observed behavior.

Theory-oriented scenarios (S1-S2) use phases 1, 2, and 5, while virtual laboratory scenarios (S3-S5) use the full sequence.

To support learners with different prior knowledge and to keep tasks feasible within limited session time, the system integrates:

- Progressive hinting, where guidance can escalate from general prompts to more explicit cues when needed;
- Checkpoint gating, where critical steps (e.g., required setup actions) must be completed correctly before the learner can proceed.

This combination aims to preserve meaningful procedural activity while preventing invalid configurations and reducing the likelihood of incomplete sessions. In theory-oriented scenarios, outputs consist of learner decisions and short explanations prompted during the lesson. In virtual laboratory scenarios, outputs additionally include confirmation of valid assembly/procedure completion and captured measurements or observations recorded during simulation. All scenarios conclude with a short debrief designed to reinforce conceptual links and support transfer to real laboratory or field contexts.

4. Scenario suite

Table 1 summarizes the five scenarios included in the VR package and outlines their instructional focus and interaction structure. Two scenarios are primarily theory-oriented, emphasizing conceptual explanation, process visualization, and procedural reasoning through guided prompts and decision checkpoints. The remaining three scenarios adopt a virtual laboratory format, in which learners progress through structured phases that include experimental stand assembly, operation of a simulated process, and capture of system outputs or measurements. Across all scenarios, interaction is designed to support stepwise exploration and reflection rather than performance assessment, enabling consistent use across different Environmental Engineering topics and instructional contexts.

Table 1. Summary of the five environmental engineering VR scenarios

Scenario	Topic / unit operation	Type	Primary learner outputs
S1	Wastewater sampling methods and techniques (DAF context)	Theory	Sampling strategy choice(s) and justification
S2	Poultry slaughterhouse WWTP process using	Theory	Explanation of treatment chain and MBR role

	MBR		
S3	Ultrafiltration (UF) for final treatment of industrial wastewater	Virtual lab	Validated stand assembly, simulation run, captured measurements/ observations
S4	Reverse osmosis (RO) for wastewater filtration	Virtual lab	Validated stand assembly, simulation run, captured measurements/ observations
S5	UV disinfection for real wastewater	Virtual lab	Validated stand assembly, simulation run, captured measurements/ observations

S1 - Wastewater sampling methods and techniques (DAF context)

This module introduces sampling purpose and representativeness through short conceptual segments and decision prompts (Figure 1). Learners select appropriate sampling approaches for given monitoring goals and justify choices, with guidance available through progressive hints and gated checkpoints for key prompts. The scenario positions sampling decisions in relation to practical treatment monitoring needs, using DAF as contextual anchoring.
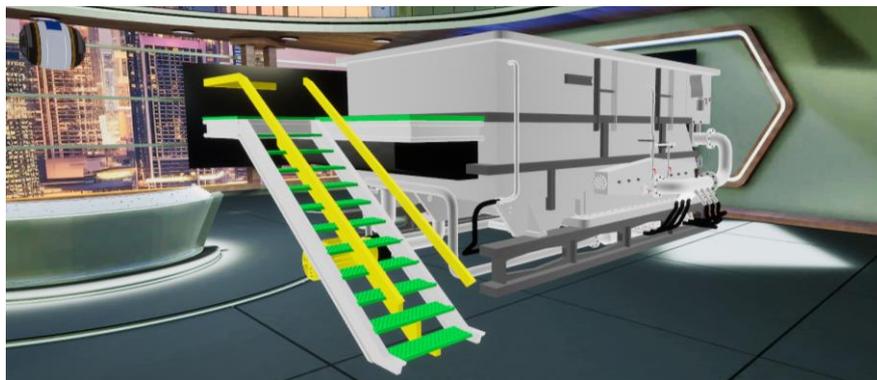

Figure 1. VR scenario view illustrating sampling decision points within a dissolved air flotation (DAF) - context wastewater treatment module

S2 - Poultry slaughterhouse wastewater treatment process using MBR

This module presents a structured walkthrough of an industrial wastewater treatment chain with an emphasis on the role of MBR technology (Figure 2). Learners follow guided explanations and respond to prompts about the function of each stage and the operational logic of MBR, including typical constraints such as process variability and membrane-related considerations. Outputs focus on a coherent explanation of the process flow and the rationale for the MBR stage.

Figure 2. VR-based membrane bioreactor (MBR) scenario illustrating process flow, membrane operation, and operational constraints

S3 - Ultrafiltration (UF) virtual laboratory

The UF scenario extends beyond theory into a lab-like workflow. Learners complete a guided assembly of an experimental stand using controllerbased manipulation, validated through checkpoint gating (Figure 3). After setup, they run the process in simulation, observe system behavior, and record required outputs. The debrief prompts connect operating choices to observed behavior to support basic interpretation.

Figure 3. VR-based ultrafiltration scenario depicting membrane separation, valve configuration, and processflow visualization

S4 - Reverse osmosis (RO) virtual laboratory

The RO scenario follows the same structure as UF (Figure 4), emphasizing correct stand setup and safe operational sequencing prior to simulation. Learners assemble the experimental stand with hints available as needed, then operate the simulated process and capture outputs/measurements. Reflection prompts focus on cause-effect reasoning between operating conditions and outcomes.
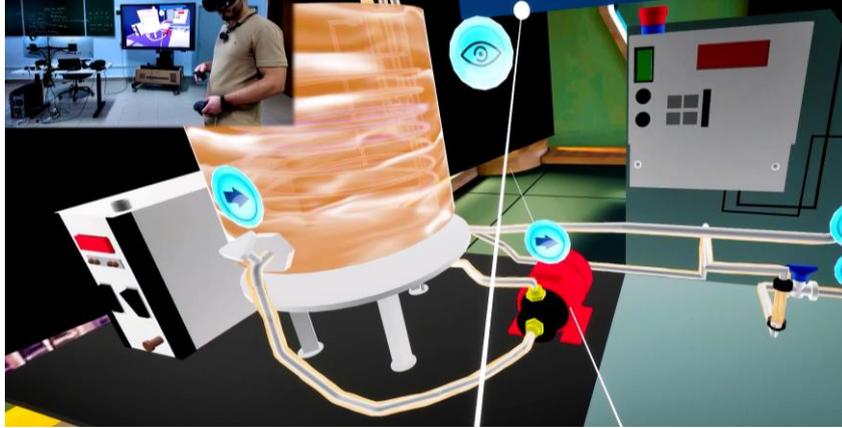
Figure 4. VR-based reverse osmosis (RO) virtual laboratory illustrating system setup, operation sequencing, and measurement points

S5 - UV disinfection virtual laboratory

The UV scenario implements guided assembly and operation of an experimental stand for UV treatment (Figure 5). Learners complete validated setup steps, run a simulated disinfection sequence, and capture outputs/observations relevant to treatment efficacy reasoning. The debrief reinforces key factors affecting UV performance and highlights transfer considerations for real laboratory application.
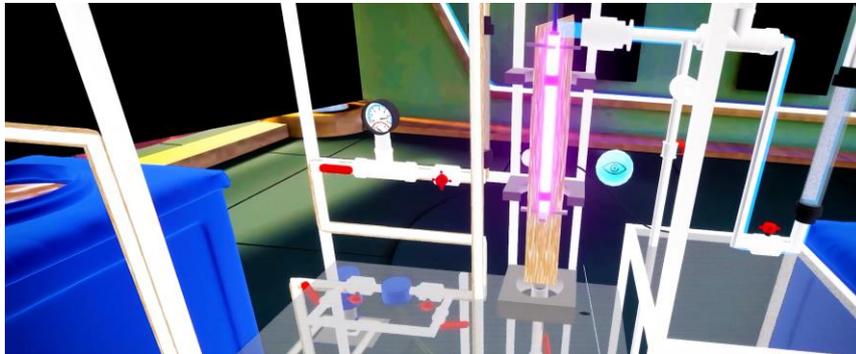

Figure 5. VR-based ultraviolet (UV) disinfection scenario illustrating experimental stand, operation sequence, and observation points

5. Evaluation

This chapter presents the results of the teacher evaluation using a mixedmethods approach (Table 2). Quantitative findings are reported first, based on descriptive statistics for the Likertscale items (Items 1-13 on a 1-5 scale) and the global ratings (Items 14-15 on a 1-10 scale), including central tendency, dispersion, and confidence intervals to summarize overall agreement and variability.

Qualitative findings are then presented from the openended questions, synthesizing recurring themes in teachers' comments to capture strengths, concerns, and improvement suggestions that may not be visible in numerical ratings. Together, these two strands provide a complementary view of perceived structure clarity, usability, and teaching readiness, and they inform the key take-aways and actionable recommendations discussed at the end of the chapter.

The teacher sample (N = 10) was intended as a feasibility and pilot usability study rather than a statistically powered experiment, in line with early-stage design validation of educational technology.

Table 2. Questionnaire Items for Assessing VR Platform

Questions
1. The application steps are logically ordered (from introduction to completion)
2. Transitions between stages are clear (you always know "what's next").
3. The lesson pace is appropriate (not too fast / not too slow).
4. The user does not feel "lost" during the experience.
5. The pre-brief sufficiently prepares the user for what follows.
6. The theoretical component is welldefined and easy to follow.
7. The practice/simulation is coherently integrated with the theory.
8. The debrief (recap/feedback) logically concludes the lesson.
9. Navigation is intuitive (buttons, menus, teleport, steps).
10. The user has sufficient control (pause, resume, repeat, back).
11. The indicators/guidance (arrows, highlighting, voice) are appropriate in intensity.
12. The structure is consistent between scenarios (you don't "learn" a new flow each time).
13. The differences between scenarios are clear and justified by objectives (not chaotic).
14. How clear is the structure overall?
15. How "teachingready" is the structure for use in a course?
16. What is the best part of the structure?
17. What is the weakest part of the structure?
18. What would you change about the sequence of stages (add/remove/reorder)?

5.1 Quantitative results

Ten teachers completed the questionnaire (N = 10). Items 1-13 used a 5point Likert scale (1 = strongly disagree, 5 = strongly agree), while items 14-15 used a 10point scale (1 = very low, 10 = very high). Overall, responses indicated very high perceived quality of the lesson structure, with consistently high central tendency and low dispersion across items (Table 3).

Table 3. Descriptive statistics of teacher ratings

Question	Mean	Std Dev	Var.	Q1	Q3	IQR	Skewness	Kurtosis	95% CI
1.	4,8	0,6	0,40	5	5	0	-3,16	10,00	[4.41, 5.19]
2.	4,9	0,3	0,10	5	5	0	-3,16	10,00	[4.70, 5.10]
3.	4,8	0,4	0,18	5	5	0	-1,78	1,41	[4.54, 5.06]
4.	4,5	0,7	0,50	4	5	1	-1,18	0,57	[4.06, 4.94]
5.	4,7	0,7	0,46	5	5	0	-2,28	4,77	[4.28, 5.12]
6.	4,9	0,3	0,10	5	5	0	-3,16	10,00	[4.70, 5.10]
7.	4,9	0,3	0,10	5	5	0	-3,16	10,00	[4.70, 5.10]
8.	4,8	0,4	0,18	5	5	0	-1,78	1,41	[4.54, 5.06]
9.	4,9	0,3	0,10	5	5	0	-3,16	10,00	[4.70, 5.10]
10.	4,8	0,4	0,18	5	5	0	-1,78	1,41	[4.54, 5.06]
11.	4,7	0,5	0,23	4,25	5	0,75	-1,04	-1,22	[4.40, 5.00]
12.	4,7	0,5	0,23	4,25	5	0,75	-1,04	-1,22	[4.40, 5.00]
13.	4,9	0,3	0,10	5	5	0	-3,16	10,00	[4.70, 5.10]
14.	9,6	0,7	0,49	9,25	10	0,75	-1,66	2,05	[9.17, 10.03]
15.	9,4	0,8	0,71	9	10	1	-1,00	-0,67	[8.88, 9.92]

Teachers rated the overall sequencing of the application as highly coherent. The logical ordering of steps showed a mean of 4.8 (SD = 0.6; 95% CI [4.41, 5.19]) and transitions between stages reached the highest mean in this block at 4.9 (SD = 0.3; CI [4.70, 5.10]). The lesson pace was also rated very positively (M = 4.8, SD = 0.4; CI [4.54, 5.06]).

The comparatively lowest score across the entire 1-5 section was for the item "The user does not feel lost" (Item 4), though it remained high (M = 4.5, SD = 0.7; CI [4.06, 4.94]) and had a wider IQR (Q1 = 4, Q3 = 5; IQR = 1), suggesting slightly more varied perceptions on user orientation than on other aspects of

structure. The pre-brief was evaluated as sufficiently preparatory (M = 4.7, SD = 0.7; CI [4.28, 5.12]). Both the clarity of the theoretical component (Item 6) and the integration of practice/simulation with theory (Item 7) achieved near-ceiling results (M = 4.9, SD = 0.3; CI [4.70, 5.10] for both), indicating strong consensus. The debrief was also rated highly (M = 4.8, SD = 0.4; CI [4.54, 5.06]).

Usability related items were rated very favorably. Navigation intuitiveness (Item 9) and scenario differences being clear/justified (Item 13) both showed M = 4.9 (SD = 0.3; CI [4.70, 5.10]). User control (Item 10) remained high (M = 4.8, SD = 0.4; CI [4.54, 5.06]). Items related to guidance intensity (Item 11) and structural consistency between scenarios (Item 12) were also rated strongly (both M = 4.7, SD = 0.5; CI [4.40, 5.00]), but displayed slightly broader spread (IQR = 0.75), implying minor differences in how teachers perceived the "amount" of guidance and the uniformity of the flow across scenarios.

On the 10point items, teachers reported very high global endorsement. Overall clarity of the structure (Item 14) scored 9.6 (SD = 0.7; CI [9.17, 10.03]) and teachingreadiness for course use (Item 15) scored 9.4 (SD = 0.8; CI [8.88, 9.92]).

These results suggest the structure is perceived as both clear and readily deployable in instructional settings. Across most 1-5 items, Q3 = 5 and IQR was 0 for many questions, indicating responses clustered at the top of the scale (ceiling effect). This is consistent with the strongly negative skewness values reported (e.g., several items around -3.16) and elevated kurtosis for some items, reflecting a peaked distribution with many maximum ratings. Practically, these patterns indicate strong agreement but also limited variability, which may reduce sensitivity for distinguishing between "very good" and "excellent" aspects of the design.

Averaging the item means for Items 1-13 yields an overall mean of approximately 4.79/5, reflecting uniformly high perceived quality of structure, transitions, integration, and usability, with the main relative opportunity area being minimizing the chance a user feels "lost" during the experience (Item 4).

5.2 Qualitative results

Q16: "What is the best part of the structure?"

Teachers' responses highlight a strong appreciation for the structure's intuitiveness and clarity, alongside its instructional value enabled by VR. Overall, participants emphasize that the lesson flow is easy to follow and that information is presented in a way that supports quick orientation and understanding, reducing the likelihood of confusion during the learning experience.

Main themes identified:
- Intuitiveness and clarity of presentation: Several teachers explicitly described the structure as "intuitive" and the delivery as "clear," suggesting that the step sequence and guidance effectively support user navigation and comprehension.

- Strong theory-practice integration through contextual VR delivery: A detailed response emphasized the "perfect integration" of theory directly into the VR practical environment (e.g., embedded informational panels, animations, and highlighted components within the virtual installation). This "see-and-understand" approach was framed as just-in-time learning, where theory appears immediately before or during the practical task-helping bridge abstract concepts and concrete application.
- Perceived pedagogical relevance and alignment with authentic learning practices: Respondents noted the value of using VR in teaching and described the lesson as grounded in "real learning practices," indicating that the structure is seen as didactically meaningful and transferable to instructional settings.
- The lesson starts as a motivational activation point: One teacher identified the beginning of the lesson as the strongest part, describing it as the activation and motivation moment-suggesting that the introduction/pre-brief effectively primes learners for the tasks that follow.
- Data note: One response was noninformative ("-") and one was ambiguous ("the last one"), so these were treated as not contributing interpretable content.

Q17: "What is the weakest part of the structure?"

Overall, teachers reported few clear weaknesses in the lesson structure. Several respondents explicitly stated that they did not identify any weak part, suggesting high overall acceptance. When limitations were mentioned, they clustered around delivery/communication issues (voice quality, pacing, and transitions) and one higherlevel pedagogical concern regarding the potential passivity of the theoretical component.

Main themes identified:
- No weaknesses perceived (dominant pattern): Multiple teachers answered "I did not identify any" or "There isn't one," indicating that-at least at a global level-the structure is perceived as robust and coherent.
- Audio/assistant delivery issues (voice, diction, pace, clarity): Several responses pointed to problems with the virtual assistant's speech output, including diction, rhythm, and word clarity. This suggests that the structure itself may be solid, but the communication layer (TTS/voiceover quality and pacing) can reduce perceived smoothness and professionalism.
- Visual/flow transitions (between images/stages): One teacher noted that transitions "from one image to another" are sometimes faulty. This indicates a usability/continuity issue that may disrupt immersion and make the experience feel less seamless.
- Theoretical phase may feel passive (interaction depth): One detailed

response highlighted a more pedagogical weakness: although theory is visually integrated, it may sometimes feel like a sequence of information panels to observe rather than actively engage with-especially if content is dense. The respondent suggested strengthening this stage with interactive comprehension checks (e.g., draganddrop labeling, short multiplechoice questions) before allowing progression to the practical simulation. This points to an opportunity to increase active processing and reduce superficial skimming.

- Data note: One entry was noninformative ("-") and one response ("lack of knowledge") is unclear in meaning and may reflect respondent uncertainty rather than a structural flaw.

Q18: "What would you change in the sequence of stages (add/ remove/ reorder)?"

Overall, responses indicate that teachers consider the current stage sequence appropriate and logically aligned with how learning should unfold. Most participants explicitly stated they would not change anything, reinforcing the quantitative pattern of very high ratings for ordering and transitions. The suggestions that did appear were targeted enhancements rather than requests for major restructuring, focusing on accessibility, authenticity, and deeper engagement.

Main themes identified:

- No change needed / sequence already logical (dominant pattern): Most teachers responded "Nothing" or emphasized that the stages are "organized in the logical order of learning". This suggests broad agreement that the current flow is coherent and instructionally sound.
- Accessibility improvement (visionrelated adaptation): One respondent suggested adding elements to support users with ophthalmological/visual impairments. This points to an opportunity to strengthen inclusivity through adjustable visual settings (e.g., text size, contrast, reduced motion, UI scaling, alternative cues).
- Increase realworld grounding (pilot station discussion): One teacher proposed including a discussion connected to real pilot stations, indicating interest in strengthening authenticity and transfer by linking the virtual sequence to real operational contexts (e.g., short case examples, "how this appears in real installations").
- Add an early lowrisk interactive preview (engagement priming): A detailed suggestion proposed adding a brief, lowstakes interactive preview at the start of the pre-brief (30-60 seconds in a simplified environment, with a small task such as identifying key equipment). The intent is to build curiosity and provide an initial mental model so that later objectives and theory feel more meaningful.
- Refine the debrief closure toward forward transfer (reordering within debrief): The same detailed response recommended ending the debrief with a futureoriented reflective question (e.g., what parameter would be

monitored first in a real installation), rather than finishing only with a recap of past actions. This would better promote reflection and transfer beyond the simulation.
- Data note: One entry was noninformative ("-"), and the rest were clearly interpretable.

6. Discussion and future work

The scenario suite was structured to cover two instructional needs that often coexist in Environmental Engineering teaching. The first need is conceptual orientation and procedural reasoning in domains where learners must make defensible choices without immediately performing physical actions, as reflected in the sampling module and the MBR process walkthrough. The second need is procedural rehearsal for unit operations that are commonly taught through laboratory workflows, reflected in the UF, RO, and UV modules. Keeping a stable lesson architecture across both types reduces switching costs and supports modular use across different course weeks.

Phase selection supports this modularity in practice. A learner can enter a scenario directly at the theory phase for revision, or repeat only the assembly and simulation phases when the goal is procedural fluency. This structure also accommodates typical laboratory scheduling constraints, where time may be sufficient for a focused drill but not for an end-to-end lesson.

Progressive hinting and checkpoint gating were implemented to manage a common tension in procedural VR lessons. Open exploration can produce inconsistent progress and invalid configurations, while rigid scripting can reduce meaningful engagement. A stepped hinting model and validation checkpoints aim to keep the workflow realistic enough to preserve sequencing logic, while maintaining task completion feasibility in supervised sessions.

The software has been implemented in a laboratory context, moving beyond a standalone development environment. The laboratory setup enables immersive VR delivery with controller-based interaction, aligned with the intended use of the scenarios as structured instructional activities rather than informal demonstrations. At this stage, the development focus shifts from feature completion to testing under real session conditions.

Testing is positioned as feasibility and user-acceptance work prior to any controlled claims about learning outcomes. The most appropriate near-term objective is to determine whether participants can complete the intended lesson phases within allocated laboratory time and whether the interaction model is perceived as usable.

A practical testing plan emphasizes three evidence streams:
1. Feasibility indicators
    o completion rate by phase and by scenario;
    o time-on-task per phase, including the use of phase selection;
    o frequency of stalls, resets, and incomplete runs;

2. Interaction and workflow indicators
   o checkpoint attempts and common failure points during assembly and operation;
   o progressive hinting patterns, including escalation frequency;
   o recurring control or UI errors observed by instructors;
3. Perception-based indicators
   o usability ratings and perceived ease of use;
   o engagement and presence ratings;
   o perceived learning value and perceived readiness for real laboratory activity;

Results should be framed as participant-reported perceptions and observed feasibility patterns, not as confirmed learning outcomes. Objective performance outcomes and comparative studies belong to the subsequent phase after usability and feasibility are stabilized.

The scenario framework is intended to support additional unit operations using the same phase model and interaction primitives. Future iterations can add new modules while preserving consistency in onboarding, guidance logic, and reporting outputs. Refinement priorities are expected to emerge from laboratory testing, particularly around phase durations, hint escalation thresholds, and checkpoint strictness to match instructor expectations and session timing.

7. Conclusion

This paper presented a VR software package for Environmental Engineering implemented in Unreal Engine with controller-based interaction and organized into five scenarios spanning wastewater sampling (DAF context), an industrial MBR-based process walkthrough, and three virtual laboratory modules for ultrafiltration, reverse osmosis, and UV disinfection. The main contribution is a reusable lesson architecture that standardizes lesson phases (pre-brief, theory, assembly, simulation/measurements, debrief) while allowing learners to start from a selected phase, supported by progressive hinting and checkpoint gating to maintain procedural validity and completion feasibility within limited session time. In addition to documenting the system design and scenario suite, a preliminary mixed-method teacher evaluation (N = 10) provided convergent evidence of high perceived structure clarity, strong theory–practice integration, and high teaching readiness, while also indicating improvement opportunities related to user orientation and communication/transition smoothness. The immediate next step is learner-based feasibility testing under authentic session constraints (completion rate and time-on-task by phase, checkpoint/hint usage patterns), followed by controlled comparative studies that incorporate objective performance measures and learning outcomes.

8. Limitations

This paper includes preliminary empirical results based on a small-scale teacher evaluation focused on usability and structural clarity, but does not yet include learner performance data or controlled experimental outcomes. Consequently, no claims are advanced regarding learning gains, retention, or comparative effectiveness versus non-VR instruction. The current contribution is limited to the documented lesson architecture and the five implemented scenarios; extension to additional unit operations and validation across learner groups remains future work. Finally, laboratory deployment depends on local VR hardware availability and instructional time allocation, which may constrain scalability across institutions.

REFERENCES

Ciolacu, M. I., Beer, R., Teichmann, D. & Binder, M. (2023) Developing future skills in engineering education for Industry 5.0: enabling technologies in the age of digital transformation and green transition. In: Auer, M.E., Langmann, R. & Tsiatsos, T. (eds.) *Open Science in Engineering. REV 2023. Lecture Notes in Networks and Systems, vol. 763*. Cham, Springer. https://doi.org/10.1007/978-3-031-42467-0_94.

Cook-Chennault, K. & Farooq, A. (2023) Student perceived value of engineering labs: a lab assessment instrument. *International Journal of Engineering Education*, 39(4), 860-876. https://doi.org/10.11591/ijere.v13i4.26660.

Coutinho, G. S., Magana, A. J. & Dias, V. D. R. (2023) A framework for the development of online virtual labs for engineering education. In: *Proceedings of the 2023 ASEE Annual Conference & Exposition*, June 2023, Baltimore, MD, USA. https://doi.org/10.18260/1-2--42396.

Grigore, P.-I. & Turcu, C.O. (2024) Impact of virtual reality on pre-university students. *Romanian Journal of Information Technology and Automatic Control*, 34(4), 99-113. https://doi.org/10.33436/v34i4y202408.

Grigore, P.-I. & Turcu, C.O. (2025) Integrating virtual reality into engineering education: an interactive application for learning mechanisms. In: *Proceedings of the International Conference on Virtual Learning*, vol. 20, pp. 155-166. https://doi.org/10.58503/icvl-v20y202513.

Grigore, P.-I. & Turcu, C.O. (2026) Evaluating the impact of virtual reality on student engagement and conceptual understanding in engineering education. *Next Research*. 3, 101172. https://doi.org/10.1016/j.nexres.2025.101172.

Hamurcu, A., Timur, Ş. & Rızvanoğlu, K. (2023) A study on the adoption of virtual reality in industrial design education. *IEEE Transactions on Learning Technologies*. 16(6), 900-913. https://doi.org/10.1109/TLT.2023.3321292.

Jindal, R., Mittal, S.K. & Bansal, A. (2023) Engineering education and the use of virtual reality: idea and possibility. In: *Proceedings of the 2nd IEEE Delhi Section Flagship Conference (DELCON 2023), Rajpura, India*. Piscataway, NJ, IEEE. pp. 1-7. https://doi.org/10.1109/DELCON57910.2023.10127272.

Parlier, J. (2024) Enhancing advanced manufacturing and engineering instruction with augmented and virtual reality (AR/VR). In: *Proceedings of the 2022 Conference for Industry and Education Collaboration (CIEC)*, Tempe, AZ. Washington, DC, American Society for Engineering Education. https://doi.org/10.18260/1-2-670-45690.

Singh, G., Mantri, A., Sharma, O. & Kaur, R. (2021) Virtual reality learning environment for enhancing electronics engineering laboratory experience. *Computer Applications in Engineering Education*, 29(1), 229-243. https://doi.org/10.1002/cae.22333.

Vergara, D., Antón-Sancho, Á., Lampropoulos, G. & García-Peñalvo, F.J. (2025) Educational use of virtual reality technologies in engineering education: the impact of the digital generation of faculty. *Education and Information Technologies*. 30, 12807-12825. https://doi.org/10.1007/s10639-025-13325-x.

Vergara, D., Fernández-Arias, P., Extremera, J., Dávila, L.P. & Rubio, M.P. (2022) Educational trends post COVID-19 in engineering: virtual laboratories. *Materials Today: Proceedings*, 49(1), 155-160. doi: https://doi.org/10.1016/j.matpr.2021.07.494.

Wang, C., Tang, Y., Kassem, M.A., Li, H. & Hua, B. (2022) Application of VR technology in civil engineering education. *Computer Applications in Engineering Education*. 30(2), 335-348. https://doi.org/10.1002/cae.22458.

Zaharia, A., Nedeff, V., Frunza, N., Nedeff, F., Bârsan, N. & Chitimuş, D. (2024b) Some practical approaches of the poultry slaughter wastewater treatment by applying physico-chemical treatment. *BIO Web of Conferences*. 122, 01022. https://doi.org/10.1051/bioconf/202412201022.

Zaharia, A., Nedeff, V., López-Ramírez, J.A., Moşneguţu, E., Bârsan, N., Lehadus-Panaite, M., Krzysztof, J. & Tomozei, C. (2024a) Scanning electron microscope analysis of polypropylene filter cartridges used in drinking water purification systems. *Water*. 16(1), 165. https://doi.org/10.3390/w16010165.