An immersive virtual reality learning environment with CFD simulations: Unveiling the Virtual Garage concept

Supplementary Information

Free access to VR application and walkthrough video

The Virtual Garage with Case\#6 is freely downloadable on GitHub: XXX (TBA)

A walkthrough video of the Case\#6 is available on YouTube: https://www.youtube.com/watch?v=Lv -Hl0eMY

The list of challenges impeding the adoption of VR in engineering education

Recently published reviews have come up with a broad list of challenges that are dramatically impeding adoption of VR in engineering education, summarized as follows:

- lacking reliable guidelines and standards in the design, development and implementation (Wang et al. 2022; Takrouri et al. 2022);
- difficulties in finding and producing relevant digital content (Wang et al. 2022; Takrouri et al. 2022);
- missing user-friendly customization and authoring tools (Ververidis et al. 2022; Takrouri et al. 2022; Horst et al. 2022);
- discouraged novice students and practitioners to adopt the technology (Huang and Roscoe 2021; Wang et al. 2022; Takrouri et al. 2022);
- language barriers (Takrouri et al. 2022);
- irrelevant and superficial user evaluation metrics obscuring underlying reasons (Lanzo et al. 2020; Gattullo et al. 2022; Takrouri et al. 2022);
- subjective and primitive data analyses (Huang and Roscoe 2021; Takrouri et al. 2022);
- weakly utilized mixed, qualitative and quantitative methodologies (Huang and Roscoe 2021; Takrouri et al. 2022);
- missing learning theories and inadequate instructional design methodologies (Soliman et al. 2021; Huang and Roscoe 2021);
- undervaluing multidisciplinary collaborations among engineers, educators and software developers (Huang and Roscoe 2021).

4C/ID and multimedia principles in the Virtual Garage concept

Table A1. demonstrates the implementation of the 4C/ID model in the Virtual Garage concept. The relevant principles are adopted from the original guideline (Kester and Merriënboer 2021). Overall, several principles of multimedia learning are applied in the components of the 4C/ID model in the Virtual Garage concept. The learning task is structured towards the sequential principle to enable a learning environment to increase the complexity progressively. We also benefit from the variability principle by using a non-linear progression across subtasks due to its positive reflection on better test scores (Van Merriënboer and Kester 2014). Besides, the supportive information is shaped by several principles related to CFD and its methodology. The multimedia and dynamic visualization principles are mainly utilized to feed students with content-specific information. Alongside these, we also improve the quality of supporting information with coherence, self-pacing, redundancy, prior knowledge activation, knowledge progression and inductive-expository principle in the modules. Likewise, procedural information is a critical element of the 4C/ID to timely guide users in the learning environment. The fading principle, modality principle, signaling principle, spatial split-attention principle and segmentation principles are spread throughout the modules to help and guide users. In addition, the part-task practice is implemented in the learning practice to get users along with the VR controllers and cognitively challenging aspects of the simulation environment. The recognize-edit-produce principle and component-fluency principle are implemented in the Virtual Garage. Finally, we also use the personalization principle in the Virtual Garage throughout a role-playing scenario. Evidence shows that learning can be more effective with the personalization principle (Van Merriënboer and Kester 2014). We only provide an informal conversation style with a human voice narration using a polite communication style to deliver both supporting and procedural information. The narration directly talks to users. We did not implement a visual object to embody the narrator’s character. Both audio and written instructions are utilized to deliver supporting and procedural information. All audio instructions are kept compulsory to listen to, even if an accompanying text is available in the same environment.

Table A1. Multimedia principles applied in the Virtual Garage concept.

Component	Principles	Examples from the Case#6 in the Virtual Garage
Learning task	Sequential	To enable a learning environment to progressively increase the complexity. For example, first, introduce different types of impellers to mix water. Then add another liquid to investigate the effect of impellers and viscosity on the mixing quality.
	Variability	A non-linear progression across subtasks due to its positive reflection on better test scores. Introduce the power consumption right after the mixing quality to provide a cost-related aspect imperative in decision-making. Then, turn back to mixing quality and examine the effect of baffle plates on the mixing quality.
Supportive information	Multimedia, dynamic visualization, coherence, self-pacing, redundancy, prior knowledge activation, knowledge progression, inductive-expository and personalization	To enable an inclusive experience to deliver complex information, the Virtual Garage inherits a set of principles considering both visual and auditory ways of communication. For example, based on the dynamic visualization principle, users do interact with 3D reactor models and animations to better comprehend components and their functionalities.
Procedural information	Fading, modality, signaling, spatial split-attention, segmentation, personalization	To enable an inclusive experience to guide learners in the educational environment, the Virtual Garage inherits a set of principles considering both visual and auditory ways of communication. For example, based on the signaling principle, users are guided with visual and auditory instructions to proceed with the learning tasks.
Part-task practice	The recognize-edit-produce principle and component fluency	In addition, the part-task practice is implemented in the learning practice to get users along with the VR controllers and cognitively challenging aspects of the simulation environment such as checking mesh quality after committing a geometric manipulation.

Guidance on simulator sickness: available design aspects

Interaction and immersion of VR should be cautiously designed to mitigate simulator sickness. In the field of VR, simulator sickness refers to any physical and mental symptoms affecting users' well-being either during or after the VR experience (Caserman et al. 2021). Literature has recently been bombarded with research on simulator sickness. Several guidelines are made available to lead developers to mitigate simulator sickness in custom VR experiences (Kourtesis et al. 2019; Saredakis et al. 2020; Caserman et al. 2021). The following aspects were taken into account in the Virtual Garage concept and accordingly implemented (Kourtesis et al. 2019; Saredakis et al. 2020):

- Hardware: not only software but also hardware can trigger simulator sickness. Commercial ones would alleviate the possibility of simulator sickness if users are guided with regard to design and operating guidelines from manufacturers.
- Display: preferably faster response, better quality, lighter weight, higher fresh rate and resolution.
- Sound: preferably spatialize sound.
- Motion tracking: preferably rapid, accurate and ergonomic.
- Navigation: preferably walking is optimal, optionally teleportation. Avoid flying.
- Ergonomic interactions: 6 degree-of-freedom (DoF) with realistic interface and preferably direct hand interactions.
- User experience: learning interactions via adequate training and time.
- Computer hardware: preferably standalone VR devices.
- Content: simplistic and realistic.
- Visual stimulation: realistic, stable, responsive and low amount of motion.
- Exposure time: Less than 10 min or higher than 20 min with simplistic content.

CFD content list and content mapping

Table A2 illustrates conceptual case studies in order with the complexity of the learning subject, aiming at teaching ultrasound intensified mixing processes in chemical engineering. Cases #5 and #6 are fully digitally produced in the Virtual Garage concept. For the rest of the cases, simulation data are available and already integrated into cross-platform environments to potentially prototype digital applications in the Virtual Garage concept.

Table A2. CFD content list.

CASE	Simulation content from COMSOL, OpenFOAM and Ansys
#1	Flow past solid objects: Karman vortex street
#2	Backward facing step: Sudden expansion
#3	T-junctions (macroscale): Mixing in process industry
#4	T- and V-junctions (milli-scale): Mixing and process intensification
#5	Water treatment basin: reactors with baffle plates
#6	(Continuous) Stirred tank reactor
#7	(Continuous) Oscillatory baffled reactors
#8	Mixing in oscillatory baffled reactors (milli-scale)
#9	Introduction to ultrasound
#10	Ultrasound in Process Intensification

#11	Ultrasound bath processes
#12	Ultrasound horn processes
#13	Ultrasound-assisted oscillatory baffled reactors
#14	Tubular continuous ultrasound-assisted crystallizer
#15	Mixed content to teach fundamentals of CFD (e.g. turbulence modeling)

The CFD content list was developed considering the prior knowledge of target students. To compile a proper list that can serve both novice and experienced students, we screened the chemical engineering curriculum at KU Leuven, Belgium. It was revealed that students can struggle with the concept of ultrasound since there are no courses given about the phenomenon, except the very superficial introduction to acoustics in the early years of undergraduate. Similarly, milli- and micro-fluidic applications may also challenge students since the concept is still mostly a matter of research, and only a very limited number of courses cover the basic aspects of such applications. Fig. A1. shows a content map that comprises content to comprehend process intensification with ultrasound for the unit operations mixing and separation. The branches highlighted with red circles indicate the content that students may lack a fundamental understanding of phenomena.

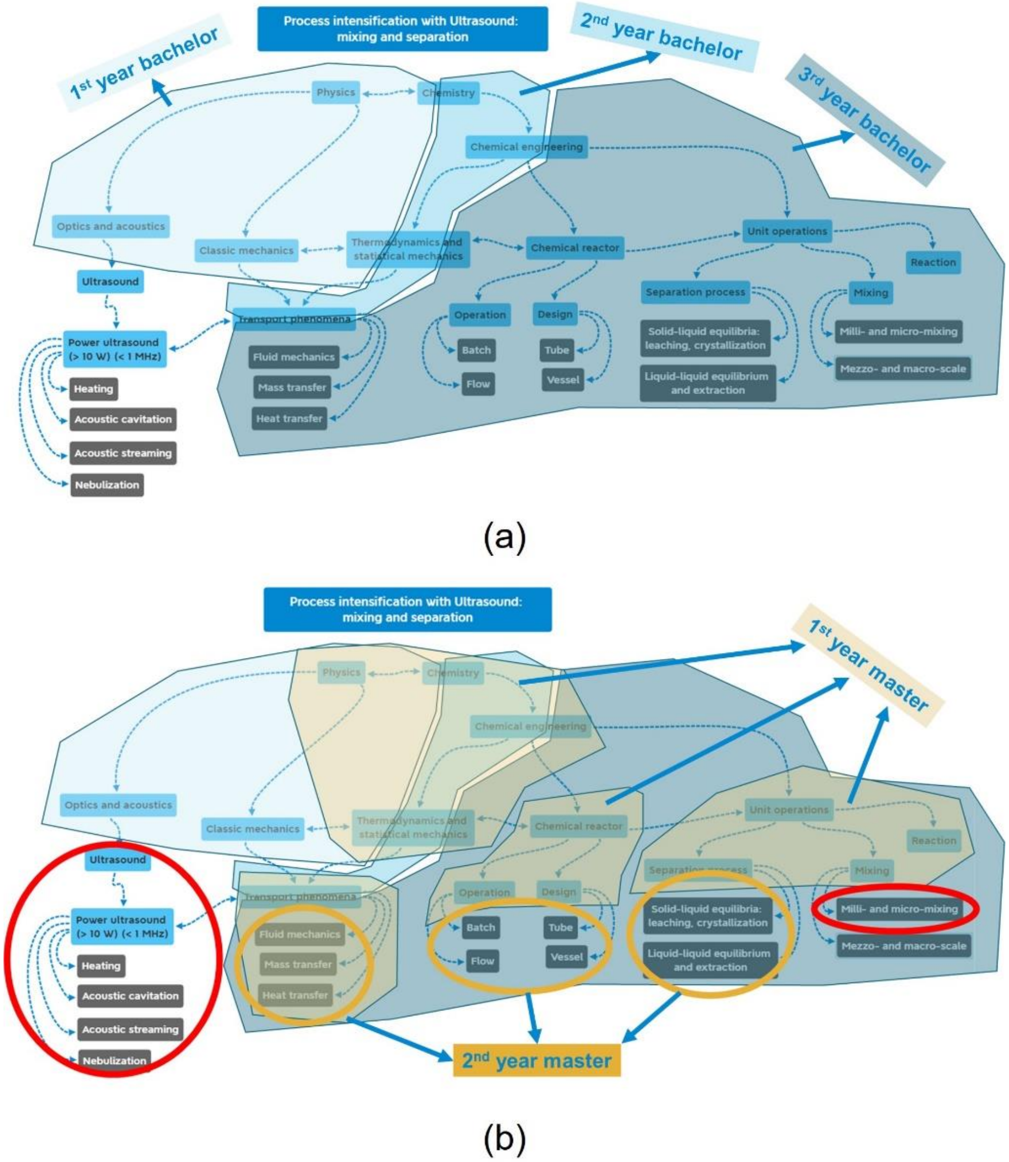

Fig. A1. Content map.

Learning objectives: Case#6 in the Virtual Garage

In Case#6, students are tasked to design a stirred tank reactor to efficiently mix liquid soap solution using design and operating parameters. Several learning objectives are given to deepen their knowledge of the effect of viscosity, type of impellers, rotational speed and baffle plates. Learning objectives of the learning module Case#6 are aligned with the learning environment. At the end of the Case#6 a student will be able to:

- Identify design and operating parameters of a stirred tank reactor
- Predict flow patterns flow patterns for different reactor configurations and working liquids
- Provide advice on how to choose right methodology to design a stirred tank reactor with CFD simulations
- Differentiate design and operating parameters based on viscosity of a working liquid
- Judge efficiency of mixing in a stirred tank reactor
- Configure a stirred tank reactor in order to efficiently high viscous Newtonian liquids such as soap

The simulation data was produced by OpenFOAM and COMSOL with incompressible, steady-state, transient and turbulent fluid flow for both 2D and 3D configurations.

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