Open Science and Supplementary Materials

This PDF file contains all supplementary materials associated with the paper **Ahsan et al.**, 2025 titled as “Towards Human-Centered VR in STEM Education: A Framework for Student–Teacher Challenges through Learning Analytics (LA) and Personalized Learning (PL)”.

This manuscript represents the first conceptual stage of a multi-phase research agenda. No empirical study, pilot, or user evaluation was carried out at this point. Future work will involve implementing and empirically validating the framework through teacher focus groups, student workshops, and VR classroom deployments. To strengthen transparency and reproducibility, we provide additional open materials associated with the conceptual design of the framework here. Although the present work represents the first, conceptual stage of a longer research agenda and therefore does not include human-subject data, we make available all artifacts that can support future implementation and replication.

1. Questionnaire Materials (Modes 1–3)

The three-mode questionnaire system was designed following User-Centered Design principles and learner-profiling methods commonly used in learning analytics and educational personalization. The goal was to elicit learner background, readiness, and instructional preferences as part of the User Model. Likert-type scales (typically 5 points) are widely used in educational and behavioral research to measure attitudes, perceptions, and self-reported experience because they provide a reliable and interpretable ordinal measure of learners’ responses (Boone & Boone, 2012).

1.1 Mode 1 (Learner Background Profiling)

Purpose: To initialize the Student Model by capturing pace, interest, prior knowledge, and skills.

1. I am familiar with the subject of this course?
   ◉Strongly Disagree ◉ Disagree ◉ Neutral ◉ Agree ◉ Strongly Agree

2. Which topics in this area do you feel most confident about? (Open)
   Response Type: Open

3. List the topics do you find challenging? (Open)
   Response Type: Open

4. My preferred learning pace is:
   ◉ Slow ◉ Moderate ◉Fast

5. The following activities help me learn best?
   ◉Reading ◉Watching demonstrations ◉Hands-on practice ◉ Group work

6. I feel motivated to learn this subject.
   ◉Strongly Disagree ◉ Disagree ◉ Neutral ◉ Agree ◉ Strongly Agree

7. Describe any prior skills relevant to this course.
   Response Type: Open

1.2 Mode 2 (Pre-Topic Awareness and Readiness)

Purpose: To assess familiarity and preparedness prior to each VR-based session.

1. I am familiar with the upcoming topic
   ◉Strongly Disagree ◉ Disagree ◉ Neutral ◉ Agree ◉ Strongly Agree

2. Which concepts of this topic do you already recognize? (Checklist/Open)
   Response Type: Open

3. I expect to face difficulties in the following areas during this lesson:
   Response Type: Open

4. The following type of support would help me before this activity:
   ◉ Summary ◉ Video explanation ◉ Worked examples ◉ Peer discussion

5. The following activities will help me learn this topic effectively:
   ◉ Exploration in VR ◉ Demonstration ◉ Guided tasks ◉ Problem solving

1.3 Mode 3 (Course Feedback and Teaching Preference Alignment)

Purpose: To refine instructional strategies and update the Teacher Model.

1. The teaching practices used in this module helped me understand the content.
   ◉Strongly Disagree ◉ Disagree ◉ Neutral ◉ Agree ◉ Strongly Agree

2. Which activity formats did you prefer in this module?
   ◉VR-based activities ◉ Individual tasks ◉ Group activities ◉ Guided practice ◉Assessments

3. The teaching methods aligned well with my learning preferences
   ◉Strongly Disagree ◉ Disagree ◉ Neutral ◉ Agree ◉ Strongly Agree

4. I prefer assessments to be organized as:
   ◉ Frequent quizzes ◉ A few major tests ◉ Project-based assessment
   ◉ Continuous assessment

5. Which instructional strategies should be used for difficult topics?
   Response Type: Open

6. Provide suggestions for improving your VR learning experience.
   Response Type: Open

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2. Reverse-Engineering Methodology (Conceptual Verification Process)

To ensure methodological transparency and reproducibility, we document the procedure used for the reverse-engineering conceptual verification through VR game. The conceptual reverse-engineering procedure in this research aligned with established software reverse engineering methodologies, including system decomposition and abstraction techniques (Chikofsky & Cross 1990; Tilley, 1998). These methods support identifying system functions, mapping operational behaviors, and aligning software components with higher-level conceptual models. We did aka mapping with our proposed framework and the VR game mechanics to theoretically verify the components with proper alignment.

The conceptual reverse-engineering process followed these steps:

1. Expert Triangulation Meeting

Involves three authors from the project:
(a) The main framework designer "Muhammad Ahsan".
(b) The VR game developer "Matheus Gonçalves".
(c) A researcher with prior reverse-engineering experience, "Laura Coura".

The meeting was conducted to trace game mechanics in the XR4Good lab at DECOM, UFOP.

2. Functional Decomposition of the VR Game

- Identified all available game components: navigation, tasks, interactions, environment cues, scoring, and system logs.
- Segmented the game into input events, user actions, feedback mechanisms, and environmental interactions.

3. Mapping Game Elements to Framework Components

Each game feature was aligned with framework layers:

- Learning Analytics Model
- Personalized Learning Layer
- User Model (Student/Teacher)
- Student Behavior Model

Example:
navigation patterns → cognitive load & spatial behavior mapping;
object interactions → performance indicators;
task completion → LA-derived metrics.

4. Identification of Missing or Future Components

- Any part of the framework that the current game did not implement was documented for future extensions (e.g., teacher dashboards, changing slides etc).

5. Conceptual Verification

- Verified that framework components *could theoretically be operationalized* in VR environments.
- No empirical behavior or user data were used.

6. Documentation and Open Sharing

- The mapping matrix, analysis notes, and conceptual alignment diagram will be shared in the open repository to support reproducibility.

The user profiling and the framework alignment with game mechanics are shown in Table .1. This process provides a transparent and reproducible blueprint for how conceptual verification was conducted.

Table.1: User profiling and Game mechanics alignment with the Framework

Components	Details
User Model – Teacher	Geography teacher
	4th to 5th grade
	Curriculum: cardinal points, maps, compass, spatial locomotion
	Strategy: find the treasure by applying geographical knowledge
User Model – Student	9 - 10 years old
	4th to 5th grade
	Lack of prior knowledge about spatial locomotion, especially maps and compass
	Interest in games
	Goals: complete the game task in time
Learning Analytics Model	Data: timer (time spent looking for the treasure), quiz, number of times digging, distance from correct digging place
	Analysis: statistics
	Reports about the analysis
Personalized Learning (PL) Model	Teacher can modify slides and add individualized hints Teacher can change the slides.
	Example: provide hints for students with ≥ 3 incorrect digging attempts (future enhancement, not yet in game)
User Behavior Model	Attention + Motivation: fast time to finish
	Cognitive load: usage of map and compass at the same time
	Attention: distractable elements in the game e.g. moving animals, environment elements
	Engagement: using the game objects (shovel, map, compass, keys and treasures)

REFERENCES:

Boone Jr, Harry N., and Deborah A. Boone. "Analyzing likert data." *The Journal of extension* 50, no. 2 (2012): 48.

Chikofsky, E.J. and Cross, J.H., 2002. Reverse engineering and design recovery: A taxonomy. *IEEE software*, *7*(1), pp.13-17.

Tilley, Scott. *A reverse-engineering environment framework*. No. CMUSEI98TR005. 1998.