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iJIM International Journal of Interactive Mobile Technologies

iJIM | eISSN: 1865-7923 | Vol. 20 No. 17 (2026) | OPEN ACCESS

https://doi.org/10.3991/ijim.v20i17.62374

PAPER

Low-Cost Mobile VR for Maintenance 4.0 Education: A Mixed-Methods Needs Analysis in Resource-Constrained Training Institutes

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ABSTRACT

Industry 4.0 has redefined the role of the maintenance technician, but public training institutes in resource-constrained settings rarely have the budget to acquire the physical equipment required for practical instruction. This paper presents an exploratory sequential mixed-methods needs analysis and technology acceptance study to establish the conceptual basis for a future low-cost virtual reality (VR) prototype. We map how key stakeholders perceive current resource barriers and evaluate their acceptance of mobile-based VR. Thirty-five semi-structured interviews (15 students, 10 teachers, and 10 industry managers) were conducted until theoretical saturation and analyzed using thematic coding. A survey using Technology Acceptance Model (TAM)-informed acceptance items was then administered to 260 respondents (170 students, 50 teachers, and 40 industry professionals). The qualitative and quantitative phases converge. Equipment shortage is strongly recognized as a pedagogical bottleneck (EQ2: M = 4.55, SD = 0.61). Mobile VR is perceived as highly useful, particularly for mitigating the risk of material damage (PU2: M = 4.68, SD = 0.50), and a low-cost smartphone-plus-cardboard option is rated as both easy to use (PEOU1: M = 4.75, SD = 0.45) and highly sustainable (COST3: M = 4.78, SD = 0.46). A one-way ANOVA indicates that teachers rate the impact of budget on pedagogy higher than students do ($p < 0.05$), while industry managers prioritize the value of mistake-tolerant training. We outline how these empirical findings constrain and guide the design of a future on-device machine learning mobile VR architecture. This study provides a context-specific, stakeholder-informed foundation for mobile technology as a primary training vehicle rather than a peripheral delivery channel, without demonstrating direct learning effectiveness at this stage.

KEYWORDS

maintenance 4.0, virtual reality (VR), needs analysis, technology acceptance model (TAM), frugal innovation, smartphone VR, on-device machine learning, engineering education

Danane, M., Ouahbi, Y., Bouzid, A., Wafi, M., Ouadi, A. E. (2026). Low-Cost Mobile VR for Maintenance 4.0 Education: A Mixed-Methods Needs Analysis in Resource-Constrained Training Institutes. *International Journal of Interactive Mobile Technologies (iJIM)*, 20(17), pp. 46–67. https://doi.org/10.3991/ijim.v20i17.62374

Article submitted 2026-04-18. Revision uploaded 2026-06-20. Final acceptance 2026-06-20.

1 INTRODUCTION

Maintenance plays a central role in modern manufacturing, and the emergence of Industry 4.0 has profoundly changed what this role consists of. In recent years, factories have moved from mechanical and electromechanical machines to cyber–physical systems that combine programmable logic controllers, networked sensors, condition-monitoring software, and embedded intelligence [1]–[3]. The function that supports these systems—now widely referred to as *Maintenance 4.0*—requires technicians who are at once practically skilled, methodical in troubleshooting, and comfortable with digital tools [4], [5].

Public training institutes are expected to produce these technicians, but in resource-constrained environments they rarely receive the budget needed to keep their workshops in line with industry [6]–[8]. Modern automated benches, hybrid powertrains, and PLC-based test rigs are expensive, and the acquisition cycle of public administration is slow [9]. As a consequence, the equipment in many workshops is obsolete, broken, or shared by groups so large that individual practice becomes the exception. The result is a well-known mismatch between what is taught and what industry expects, and this mismatch has been observed across several engineering-education contexts in recent years [10]–[12].

Virtual reality (VR) has been widely proposed as a way to close this gap. By placing learners in interactive three-dimensional environments, VR allows them to manipulate virtual machines, run procedures, and experience failures without any safety or financial risk [13]–[17]. However, almost all the published evidence has been generated with high-end head-mounted displays such as the HTC Vive, the Meta Quest, or the Microsoft HoloLens, and these systems are often deployed in well-funded research laboratories or industrial training centers [18], [19]. Although the technology acceptance model (TAM) of Davis [20] and its extensions [21]–[24] have been used to study VR adoption, few studies have addressed the specific problem of public institutes whose annual workshop budget is barely sufficient to buy a single high-end headset [25], [26].

This paper addresses this gap by presenting an exploratory sequential mixed-methods study. Rather than empirically testing the educational performance or skills transfer of a completed VR system, this study is structured as **a needs analysis, stakeholder acceptance study, and design-framing investigation**. It evaluates how students, teachers, and industry professionals perceive current training bottlenecks and assesses their acceptance of low-cost, smartphone-based VR.

To clarify our contribution, we do not evaluate an implemented software system or measure learning outcomes. Instead, this study establishes the systematic, empirical parameters required to justify and structure a low-cost, mobile-centric VR architecture. This work demonstrates that the surveyed stakeholders perceive an equipment shortage as a critical educational barrier and accept smartphone-based VR as a highly realistic and sustainable direction in the studied context. We then use these empirical findings as direct design constraints to propose a future software architecture that incorporates on-device machine learning.

Three research questions guide the work:

RQ1. How do students, teachers, and industry managers perceive the current limitations of maintenance training (equipment shortage, school–industry mismatch) with respect to the requirements of Industry 4.0?

RQ2. To what extent is VR perceived as a potential means to address these material constraints and support the pedagogical quality of maintenance training?

RQ3. What conditions (cost, accessibility, ergonomics) must a VR solution meet in order to be adopted in resource-constrained training environments?

The rest of the paper is organized as follows. Section 2 reviews the literature on Maintenance 4.0, on VR in engineering education, and on TAM. Section 3 describes the mixed-methods design, the participant characteristics, the ethical safeguards, and the development of the instruments. Section 4 reports the qualitative and quantitative findings. Section 5 interprets these findings, outlines the limitations, and presents the proposed smartphone-VR and on-device machine learning architecture as a future design implication. Section 6 summarizes the contribution and outlines the follow-up study.

2 LITERATURE REVIEW

The literature relevant to this study comes from three streams: the evolution of maintenance under Industry 4.0, the use of VR in engineering education, and the modeling of technology acceptance. This section reviews each stream in turn and ends with the gap that the present paper is designed to address.

2.1 Maintenance 4.0 and the technician's new role

The Industry 4.0 paradigm has been described as the convergence of cyber-physical systems, the Industrial Internet of Things, cloud computing, and big-data analytics [27], [28]. Within this paradigm, maintenance has shifted from corrective and preventive practices towards condition-based and predictive ones, in which sensor data and machine learning play a central role [29]–[31]. Silvestri et al. [32], Pettersson et al. [5], and Benhamza Hlihel et al. [4] review this transformation and underline that the new technician must combine three families of competence: mechanical and electromechanical knowledge, digital and data-handling skills, and procedural rigor. In addition, Aljohani et al. [33] and Gilic and İnandi [7] note that vocational and higher technical education has not yet caught up with this profile and that the gap is particularly visible in countries where public training budgets are limited.

A second body of work links the school–industry gap to the lack of hands-on practice. Maintenance is, in essence, a procedural activity: diagnostic reflexes, sequencing of operations, and motor coordination are acquired through repetition on real or sufficiently realistic equipment [34], [35]. Spöttl and Windelband [36], Aljohani et al. [33], and Xie et al. [37] report that engineering graduates often arrive on the production floor with strong theoretical foundations but weak practical reflexes, and they identify the lack of access to sufficiently modern training equipment as the dominant cause. Similar observations have been made in automotive maintenance, in advanced manufacturing, and in industrial automation, where the rate at which technologies evolve makes any physical investment quickly obsolete [5], [38], [39].

2.2 VR in engineering and maintenance education

Virtual reality has been used in engineering and industrial training for almost two decades, and the evidence on its pedagogical value has accumulated. Radianti et al. [40] present a systematic review of immersive VR applications in higher education and report consistent gains in engagement, motivation, and procedural learning across a wide range of domains. Evaluating VR applications for industrial and safety training reveals three primary benefits that recur throughout the literature: a controlled environment [41]; a "freedom to fail" safely without consequences [42]; and the capacity for unlimited repetition to build procedural muscle memory [43]. Farina et al. [44] compared a VR-based maintenance procedure with traditional video-based training and reported faster task completion and fewer errors in the VR group; a similar benefit was reported by Górski et al. [45] for safety-related maintenance procedures.

These benefits, however, have been generated almost exclusively with high-end equipment: tethered headsets, dedicated workstations, and motion-tracked controllers. The total cost of ownership of such systems includes the headset (often above US$500), a graphics-capable computer, the software licenses, and the IT support needed to keep the system running. In a public institute whose annual workshop budget is in the region of a few thousand US dollars, this combination is simply out of reach [46].

An emerging stream of research has investigated low-cost, smartphone-based VR and mobile learning. The broader mobile learning literature confirms that smartphones can effectively deliver interactive, hands-on learning experiences even in resource-constrained or vulnerable contexts [47], [48], demonstrating that free visual programming environments can successfully facilitate hands-on technical learning by leveraging the students' own mobile devices [49]. Specifically for VR, Papanastasiou et al. [50] reviewed state-of-the-art VR/AR applications across K–12 and higher education and highlighted the growing ecosystem surrounding smartphone-based immersive technologies. The review emphasized that VR/AR environments can improve learning outcomes, engagement, and problem-solving skills while reducing infrastructural barriers associated with traditional systems. However, limited attention has been given to the application of low-cost VR solutions in vocational maintenance training contexts.

Recent literature has increasingly highlighted this scalability issue. As noted in a 2025 systematic review of VR in education, mobile VR platforms offer highly scalable and cost-effective alternatives that overcome geographical and infrastructural barriers without requiring specialized, high-end equipment [51]. Furthermore, recent evaluations of Google Cardboard-based frameworks confirm that ultra-low-cost mobile VR can effectively deliver immersive interactive presentations and simulations, democratizing access to complex technical scenarios in resource-constrained educational contexts [52], [53].

2.3 TAM

To analyze user acceptance in a rigorous and reproducible way, the present study draws on the TAM introduced by Davis [20]. TAM postulates that the actual use of a technology is driven by the user's *Behavioral Intention* (BI), which is in turn determined by two beliefs: *Perceived Usefulness* (PU) and *Perceived Ease of Use* (PEOU). The model has been extended several times—most notably in TAM2 [21] and in domain-specific TAM models for VR [22]—and it is now a standard reference for educational-technology adoption studies.

Recently, TAM has been widely used to assess the viability of immersive technologies for specialized training. For example, recent studies have successfully extended TAM to evaluate immersive VR learning in vocational high schools, demonstrating that PEOU and PU strongly predict students' BI to adopt VR for hands-on technical skills [54]–[56]. However, applications of TAM specifically to frugal, mobile-based VR in the context of Maintenance 4.0 remain scarce, underscoring the necessity of the current study.

2.4 Research gap

Three observations follow from this review. First, the requirements of Maintenance 4.0 in terms of practical skills are well documented, and the mismatch between what is taught and what industry expects is well established [32], [57]. Second, VR is consistently presented as a credible answer to this mismatch, mainly because of the right to fail and the unlimited repeatability it offers [40], [58], [59]. Third, the empirical evidence has been produced with equipment whose total cost of ownership is incompatible with the budget of public institutes in resource-constrained settings, and the academic attention paid to the low-cost alternative is comparatively limited [50]. To the best of our knowledge, no study has so far combined (i) the perspectives of the three main stakeholders of maintenance education and (ii) a TAM-informed assessment of *low-cost, smartphone-based* VR for Maintenance 4.0 training. The present work addresses that gap.

3 METHODOLOGY

3.1 Research design

An exploratory sequential mixed-methods design [60] was adopted. The qualitative phase came first, with the aim of mapping how stakeholders perceive the current state of maintenance training and the potential of VR. The quantitative phase came second, with the aim of assessing these perceptions on a larger sample using TAM-informed acceptance items. The qualitative phase therefore informed the construction of the questionnaire, and the quantitative phase provided statistical weight to the qualitative themes. The overall design is shown in Figure 1.

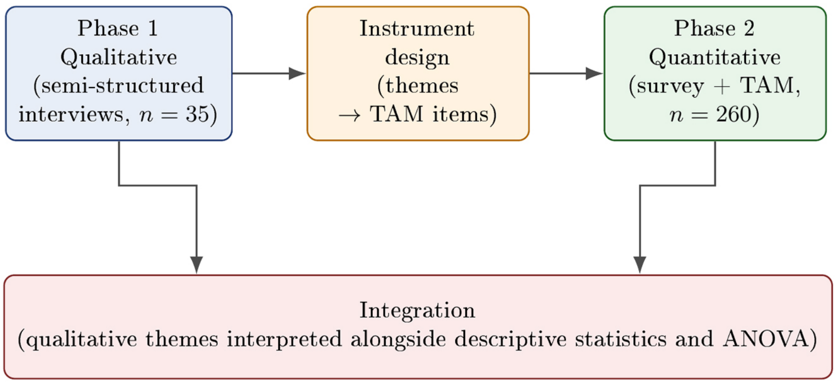

Fig. 1. Exploratory sequential mixed-methods design used for the study

3.2 Phase 1: Qualitative interviews

Context and participants. The qualitative phase was conducted across public technical and vocational training institutes in Morocco. Thirty-five semi-structured interviews were conducted with three groups of stakeholders: 15 students, 10 teachers, and 10 industry managers. The inclusion and exclusion criteria were defined to ensure representative feedback:

- **Students:** must be enrolled in a public, two- or three-year technical maintenance degree program (such as electromechanics, automotive maintenance, or industrial automation) and must have completed at least one full academic year. Students in purely theoretical programs were excluded.
- **Teachers:** must have at least two years of active experience teaching practical maintenance workshops or automation subjects in public institutes. Part-time administrative staff without teaching loads were excluded.
- **Industry managers:** must actively manage maintenance departments, production facilities, or technical recruiting in industrial companies that regularly recruit from public training institutes. Managers without direct technical hiring oversight were excluded.

The composition of the qualitative sample is detailed in Figure 2(b).

Procedure and instrument development. The semi-structured interview guide was drafted by the primary research team based on gaps identified in the literature, focusing on physical equipment constraints, the school-industry technology gap, and expectations surrounding low-cost virtual simulations. To verify face and content validity, the interview guide was reviewed and piloted with two external engineering education experts.

Each interview lasted approximately 45 minutes, was conducted online via Microsoft Teams by the primary authors, and was recorded with participant consent. The interviewers had no prior professional or personal relationships with the participants; contact was established through formal institutional letters of introduction. The questions were open-ended and adapted to each profile, so managers commented on diagnostic reflexes, teachers on workshop management, and students on their lived experience of practical works.

Analysis. All interviews were recorded with the consent of the participants, transcribed verbatim, and imported into NVivo. A thematic analysis was performed using a systematic three-stage coding process: initial open coding (to identify primary concepts), axial coding (to group concepts into categories), and selective coding (to synthesize the final core themes).

To ensure consistency, a hybrid inductive–deductive coding approach was used, establishing initial deductive codes from the literature before allowing inductive codes to emerge from the data. Two researchers independently coded a subset of 10 transcripts, randomly selected and stratified across the three cohorts (four students, three teachers, and three managers). The inter-rater agreement was assessed, yielding a Cohen's Kappa of 0.84, which is considered highly consistent; minor discrepancies were resolved through discussion with a third researcher. Theoretical saturation was tracked independently for each of the three cohorts using Guest's operational guidelines: recruitment and coding within a specific cohort ceased when three consecutive interviews within that cohort yielded no new thematic codes. To preserve anonymity, participants are referred to as Student #1–#15, Teacher #1–#10, and Manager #1–#10.

3.3 Phase 2: Quantitative survey

Instrument development. Building on the qualitative findings, a structured questionnaire was developed. Section 1 collected demographic data. Section 2 assessed perceptions of equipment shortage. Section 3 evaluated user acceptance through

TAM-informed items adapted from the scales of Davis [20] and Venkatesh and Davis [21] to fit the VR context without formally validating the structural pathways of the original TAM model. Section 4 evaluated cost sensitivity relative to hardware requirements.

To evaluate the statistical reliability of the questionnaire as an exploratory acceptance instrument, we report internal consistency (α) only for the multi-item scales. Because PEOU1 and BI1 are measured using single, conceptually distinct items to maintain survey brevity, reporting an aggregated alpha or calculating Composite Reliability (CR) and Average Variance Extracted (AVE) for these constructs is not methodologically appropriate. Therefore, we rely on Cronbach's alpha (α) to demonstrate internal consistency for the multi-item scales:

- **Equipment Shortage (EQ) (4 items):** $\alpha = 0.81$
- **Perceived Usefulness (PU) (2 items):** $\alpha = 0.84$
- **Cost Sensitivity (COST) (3 items):** $\alpha = 0.85$

All constructs exceeded the recommended threshold ($\alpha \geq 0.70$), confirming scale reliability. The exact wording of the survey items is detailed in Table 2.

Participants and recruitment. The questionnaire was distributed online across five public Technical and Vocational Education and Training (TVET) centers in Morocco. For the student cohort, the survey link was distributed via the universities' official email lists and established student WhatsApp groups. Industry managers were purposively recruited through LinkedIn and the primary researchers' professional networks. To prevent duplicate submissions, institutional email verification was enforced. Speedrunning was controlled by excluding responses completed in under 150 seconds (determined during piloting as the absolute minimum time required to read and answer all items). Out of 278 total submissions, 18 responses were removed (12 incomplete, 6 completed in an unfeasibly short timeframe), leaving a final sample of 260 valid responses. The survey and interview cohorts were drawn from the same broader institutional networks to ensure contextual transferability, but direct qualitative interviewees were excluded from taking the quantitative survey to ensure sample independence. The final quantitative sample comprised 170 students (65.4%), 50 teachers or trainers (19.2%), and 40 industry professionals (15.4%). The composition of the sample is shown in Figure 2.

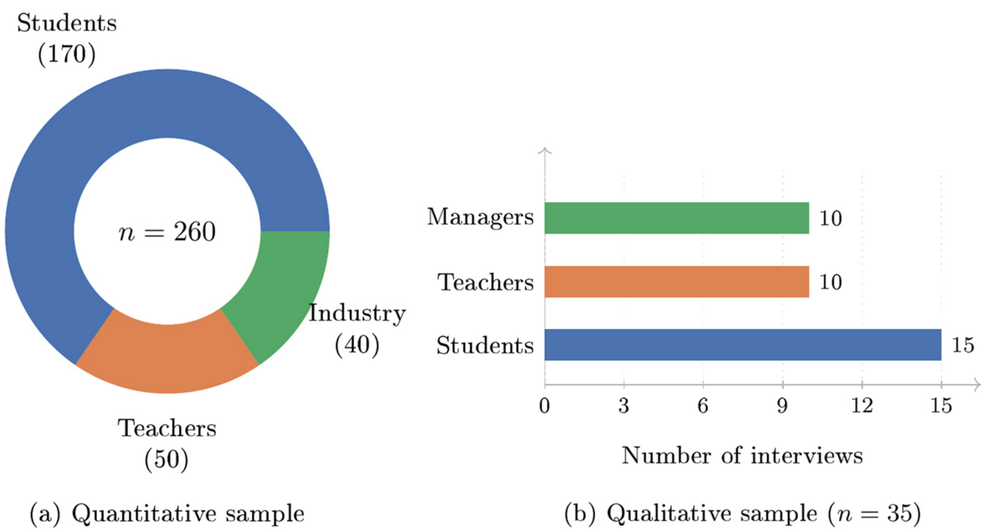

Fig. 2. Composition of the two samples: (a) Quantitative sample, n = 260; (b) Qualitative sample, n = 35

Analysis and statistical software. Data were analyzed using SPSS (v28.0) and R. Beyond descriptive statistics, a one-way analysis of variance (ANOVA) was conducted on three key "sentinel" items (EQ3, PU2, COST3) to evaluate statistically significant differences among the three stakeholder groups. Homogeneity of variances was verified using Levene's test, which was non-significant for all analyzed items ($p > 0.05$). We report the exact F-statistics, degrees of freedom (df), exact p-values (p), and effect sizes (partial eta-squared, η_p^2). Pairwise comparisons were performed using Tukey's Honestly Significant Difference (HSD) post-hoc test.

3.4 Mixed-methods integration

The two phases were integrated at the interpretation stage. Each construct of the questionnaire was traced back to one or several themes of the qualitative analysis so that the quantitative pattern could be read as a confirmation, a nuance, or a contradiction of the qualitative findings. This integration strategy is consistent with the exploratory sequential design [60] and allows the paper to move from isolated stakeholder voices to a tested set of stakeholder positions.

3.5 Ethics and integrity

No formal written ethics waiver was issued. The determination that formal approval was not required was made by the authors in consultation with the relevant department heads, in accordance with institutional guidance for minimal-risk anonymous educational research. Nevertheless, the study was conducted in strict accordance with the ethical principles of the Declaration of Helsinki.

Informed consent was obtained electronically from all survey respondents prior to access to the instrument, and verbal informed consent was obtained and recorded from all qualitative interview participants. Participants were explicitly informed of their right to withdraw at any stage without consequence. To ensure complete anonymity, all direct personal identifiers were removed from the qualitative transcripts and replaced with alphanumeric pseudonyms (e.g., Student #1, Teacher #3). All digital qualitative transcriptions and quantitative survey datasets were maintained on an encrypted, password-protected local drive accessible only to the primary research team.

4 RESULTS

This section reports the findings of the two phases. The qualitative results are summarized first, around the three themes; the quantitative results follow, organized by construct; and a short integration paragraph brings the two phases together. The detailed numerical values are given in Table 2 and Figure 3.

4.1 Phase 1 – Qualitative findings

The thematic analysis of the 35 interviews produced a coherent picture across the three groups of stakeholders. Table 1 summarizes the dominant position and the divergent opinions for each theme.

Table 1. Thematic summary of qualitative interviews (n = 35; saturation reached)

Theme	Profile	Dominant Position	Nuances/Divergent Opinions
1. School-Industry gap	Managers (n = 10)	8/10: new recruits lack diagnostic reflexes on complex 4.0 machines.	2/10 noted that theoretical knowledge and mathematical foundations are solid.
	Teachers (n = 10)	9/10: very hard to teach Industry 4.0 with obsolete physical equipment.	1/10 mentioned that the national curriculum itself is too slow to update.
	Students (n = 15)	12/15: feel theoretically prepared but anxious about real practice.	3/15 felt confident, but only on the legacy machines available at school.
2. Equipment shortage	Managers (n = 10)	10/10: industry is forced to act as a secondary school.	—
	Teachers (n = 10)	8/10: severe bottleneck during practical works; passive learning.	2/10 use 2D simulation but find it insufficient for spatial understanding.
	Students (n = 15)	14/15: practical sessions are too short and crowded, and equipment is often broken.	1/15 reported that, even when machines work, fear of breaking limits exploration.
3. VR vision and cost barrier	Managers (n = 10)	9/10: VR is exceptional for SOPs and safety lockouts.	1/10 worried about the IT maintenance of VR headsets.
	Teachers (n = 10)	10/10: traditional VR (≥US$500) is impossible for public budgets.	All 10 interviewed teachers agreed that low-cost/BYOD is the only viable path.
	Students (n = 15)	13/15: highly enthusiastic about smartphone (cardboard) VR at home.	2/15 worried about smartphone battery life and overheating.

Theme 1 – the school–industry gap. The interviews revealed a strong agreement across the three sampled groups: while students have a solid theoretical foundation, they lack the diagnostic reflexes and the troubleshooting logic that real industrial situations demand. Industry managers linked this gap directly to the difficulty of integrating new recruits in modern production lines. Manager #3, for example, stated: *"They know the math and the theory behind automated systems, but when they face a real production line that is stopped, they freeze. They lack the diagnostic reflexes that only come with practice."* Teachers traced the same gap to the obsolescence of their workshops; in the words of Teacher #2, *"We are teaching 2025 automotive technology, like hybrid engines and advanced sensors, but our workshops only have mechanical engines from 2010. The gap is huge."* Students reported the experience from the inside; Student #4 said: *"I have high grades in electromechanics theory, but I am terrified of making a mistake on a real expensive machine during my future internship because I have rarely touched one."*

Theme 2 – the severe impact of equipment shortage. An equipment shortage emerged as the single most important pedagogical barrier. Eight of the ten teachers reported a severe bottleneck during practical works that turns most sessions into observation sessions. Teacher #5 described having *"20 students for one functional automated testing bench"* and putting them in groups of five, where one student manipulates the machine while the others watch. Administrative cycles further extend the problem, as Student #1 explained: *"When a component breaks in the workshop, it takes months to get a replacement due to public administration processes. During that time, we just do paper exercises."* The downstream consequences are felt by industry; in the words of Manager #1, *"Because schools lack equipment, the industry has to act as the training center. We lose three to six months just teaching them the physical realities of the machines."*

Theme 3 – VR as a solution and the financial barrier. VR was widely perceived by the interviewed stakeholders as a credible pedagogical answer, primarily because it offers a controlled environment in which mistakes have no financial or physical consequences. Manager #4 emphasized the operational side of this argument: *"If they* *could practice standard operating procedures and safety lockouts in VR before touching our real machines, it would save us a lot of time and reduce accident risks."* The same managers and all ten teachers, however, raised an unambiguous concern about the cost of high-end VR. Teacher #1 captured this position in a single sentence: *"VR is a dream for us. But when I see a headset costs US$500, plus a gaming PC to run it, it is impossible. My annual budget for the whole workshop is barely US$2,000."* In contrast, the students reacted enthusiastically to the idea of using their own smartphone with a cheap cardboard headset. Student #5 said: *"We all have good smartphones. If the school gives us a cheap cardboard headset and I can download the engine simulation app to practice at home before the exam, I would 100% use it. It turns theory into a video game."*

Synthesis. Three positions emerge from the qualitative phase: (i) the school–industry gap is real and is felt across the three groups; (ii) equipment shortage is the dominant pedagogical barrier in public institutes; and (iii) VR is desired, but only a low-cost form of VR is seen as realistic for public integration.

4.2 Phase 2 – Quantitative findings

The questionnaire was administered to 260 respondents. The descriptive statistics are reported in Table 2, and the corresponding means and standard deviations are visualized in Figure 3. Means above 4.0 on a five-point scale indicate that the majority of respondents agreed or strongly agreed with the statement.

Table 2. Exact item wording, descriptive statistics, and reliability parameters of the questionnaire (n = 260) (Likert scale 1–5)

Construct	Item Code	Exact Wording of Survey Statement	Mean	SD
Equipment Shortage (α = 0.81)	EQ1	The physical equipment in our workshop is outdated compared to Industry 4.0 standards.	4.38	0.76
	EQ2	There is a severe lack of opportunity for individual hands-on practice during classes.	4.55	0.61
	EQ3	Budget constraints directly lower the pedagogical quality of practical training.	4.46	0.69
	EQ4	I am/students are afraid of damaging expensive hardware during practical tasks.	4.15	0.88
PU (α = 0.84)	PU1	Virtual simulations would significantly improve the understanding of complex maintenance SOPs.	4.51	0.58
	PU2	VR would provide a valuable, safe environment where making mistakes has no financial cost.	4.68	0.50
PEOU and Intention	PEOU1	Using an app on my own smartphone with a US$10 cardboard headset would be easy to learn and use.	4.75	0.45
	BI1	I would intend to use a low-cost smartphone VR application frequently if made available.	4.42	0.73
Cost Sensitivity (α = 0.85)	COST1	Deploying high-end VR headsets (≥US$500) is financially impossible for public institutes.	4.80	0.42
	COST2	I would gladly use my personal smartphone for educational VR simulations to reduce costs.	4.61	0.55
	COST3	A low-cost smartphone-based VR setup is more realistic and sustainable than high-end headsets.	4.78	0.46

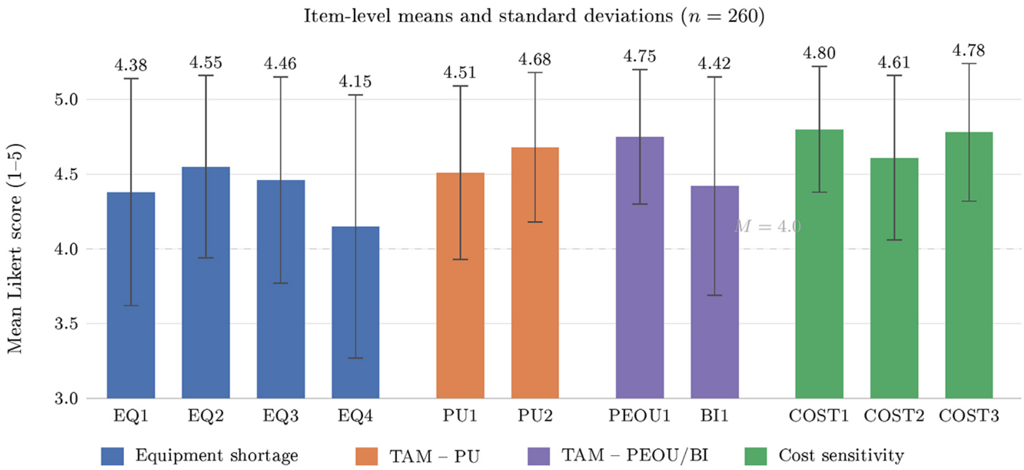

Fig. 3. Item-level means and standard deviations across the four constructs of the questionnaire (n = 260)
Note: The dashed line marks the agreement threshold M = 4.0.

Equipment shortage. The four items in this construct received consistently high scores. The lack of individual hands-on practice (EQ2: M = 4.55, SD = 0.61) is the most strongly endorsed item of the block, followed by the negative effect of budget constraints on pedagogical quality (EQ3: M = 4.46, SD = 0.69) and the perceived obsolescence of the equipment (EQ1: M = 4.38, SD = 0.76). The fear of damaging real equipment during practical sessions also received clear support (EQ4: M = 4.15, SD = 0.88). These four scores, taken together, provide statistical weight to the qualitative findings: equipment shortage is perceived as a primary, unresolved bottleneck within the studied public training institutes.

TAM – PU. PU reached high consensus. Respondents agreed that VR simulations would improve the understanding of complex maintenance procedures (PU1: M = 4.51, SD = 0.58), and they agreed even more strongly that VR provides a safe environment in which mistakes have no financial or physical consequences (PU2: M = 4.68, SD = 0.50). The low SD on PU2 indicates that this position is shared within our sample with little variability.

TAM – PEOU and BI. PEOU reached a high mean score (PEOU1: M = 4.75, SD = 0.45). This shows that respondents do not expect significant usability barriers with a smartphone-based VR application, which aligns with their daily familiarity with smartphones. BI to use such an application frequently for learning or teaching is also strong (BI1: M = 4.42, SD = 0.73).

Cost sensitivity. The three cost items produce a highly uniform pattern. Respondents agree that high-end VR headsets are financially impossible to integrate into the daily public-education system (COST1: M = 4.80, SD = 0.42). At the same time, they express a strong willingness to use their personal smartphone combined with a cheap cardboard headset (COST2: M = 4.61, SD = 0.55). The most strongly endorsed item of the entire questionnaire is COST3 (M = 4.78, SD = 0.46), which states that a low-cost smartphone VR solution is more realistic and sustainable for public institutes than expensive VR hardware. The very low SDs on COST1 and COST3—0.42 and 0.46, respectively—indicate that this position represents strong agreement across the surveyed respondents.

Between-group differences (ANOVA). The one-way ANOVA was performed on the three sentinel items (EQ3, PU2, and COST3) across the three stakeholder groups (Students, n = 170; Teachers, n = 50; Industry, n = 40). The statistical results indicate:

- **EQ3 (Budget impacts pedagogy):** a statistically significant difference was found between groups, $F(2, 257) = 3.84$, $p = 0.023$, $\eta_p^2 = 0.029$. Tukey's HSD post-hoc tests revealed that Teachers (M = 4.78, SD = 0.42) rated the negative impact of budget on pedagogy significantly higher than Students (M = 4.32, SD = 0.78; p = 0.018). Industry Managers (M = 4.55, SD = 0.60) did not differ significantly from either group (p > 0.05).

- **PU2 (Right to fail value):** a statistically significant difference was identified, F(2, 257) = 5.81, p = 0.003, $\eta_p^2 = 0.043$. Tukey's HSD post-hoc test indicated that Industry Managers (M = 4.85, SD = 0.36) rated the safe-failure potential of VR significantly higher than Students (M = 4.62, SD = 0.54; mean difference = 0.23, 95% CI [0.08, 0.38], adjusted p = 0.002). However, the post-hoc comparison between Teachers (M = 4.66, SD = 0.48) and Students (M = 4.62, SD = 0.54) was not statistically significant (mean difference = 0.04, 95% CI [–0.14, 0.22], adjusted p = 0.884). Similarly, the difference between Industry Managers and Teachers was not statistically significant (mean difference = 0.19, 95% CI [–0.02, 0.40], adjusted p = 0.091).
- **COST3 (Low-cost VR best fit):** no statistically significant difference was observed, F (2, 257) = 0.45, p = 0.638, and $\eta_p^2 = 0.003$. All three groups converged with high consensus on the sustainability of a low-cost smartphone-based approach (Students M = 4.72, SD = 0.48; Teachers M = 4.86, SD = 0.35; Industry Managers M = 4.80, SD = 0.41).

These results are illustrated in Figure 4.

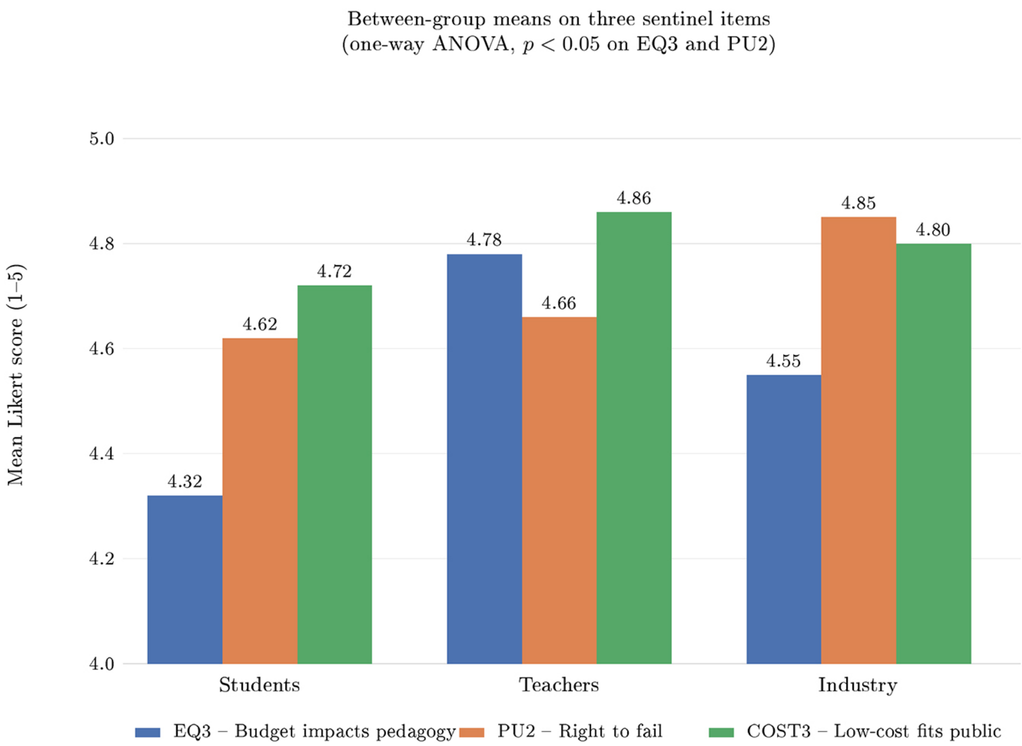

Fig. 4. Between-group means on three sentinel items

Notes: A one-way ANOVA shows that teachers rate the impact of budget on pedagogy significantly higher than students (p < 0.05) and that industry managers rate the value of the right to fail highest. All groups converge on COST3.

4.3 Mixed-methods integration

The quantitative pattern corroborates the qualitative themes. The position expressed by Teacher #1 and Student #5—that high-end VR is unaffordable and that smartphone VR is desired—is strongly supported within our sample. Furthermore, the ANOVA shows that, although the three groups prioritize different aspects depending on their role, they end up at the same point on the cost question. The right to fail is most valued by industry, the impact of budget is most acutely felt by teachers, and ease of use is universally seen as unproblematic with a smartphone form factor; but no group considers high-end VR to be a realistic solution.

5 DISCUSSION

The aim of this study was to investigate how the sampled stakeholders of maintenance education perceive the current limitations of practical training and to what extent VR—particularly low-cost VR—could be a credible answer in resource-constrained settings. Three implications follow from the integrated results, and each is discussed in turn in the light of the literature and of the field reality of public institutes.

5.1 The pedagogical bottleneck in Maintenance 4.0

The first implication is that the pedagogical bottleneck of Maintenance 4.0 is primarily related to equipment access rather than curriculum content. The very high score on EQ2 (M = 4.55, SD = 0.61) and the qualitative reporting of high-occupancy benches describe an environment in which practical learning often becomes passive. This observation aligns with the analysis of Hazrat et al. [61], who argue that the rapid evolution of Industry 4.0 technologies makes purely physical infrastructure investments financially unsustainable for public higher education institutions and with the school–industry gap reported by Spöttl and Windelband [36] and Khan and Mourad [62]. It also reinforces a point that recent studies on maintenance training have increasingly emphasized: maintenance is, in essence, a procedural and psychomotor activity, and procedural skills are acquired through individual repetition rather than through observation [63]–[65]. When repetition is constrained by the lack of equipment, theoretical knowledge cannot easily be converted into practical diagnostic reflexes.

5.2 Technology acceptance and the right to fail

The second implication concerns the structure of acceptance itself. The TAM scores indicate that PU2 (M = 4.68, SD = 0.50) is consistently higher than PU1 (M = 4.51, SD = 0.58), and the ANOVA shows that managers value the right to fail most. This pattern suggests that, in the present sample, VR is accepted not because it is expected to teach conceptually better than physical systems, but because it is expected to remove the cost and risk of material damage. This finding is in line with the trial-and-error literature on extended reality, which reports that the reduction of the cognitive and physical cost of failure increases exploration and, in turn, procedural retention [66]. It also lends support to the more general argument of Sagnier et al. [22] that PU is a dominant lever of user acceptance in immersive environments.

5.3 The frugal-innovation imperative

The third implication, and the primary guideline for the subsequent development of this study, concerns the physical form that VR should take in public institutes. The score on COST1 (M = 4.80, SD = 0.42) is the highest of the entire questionnaire, and the low standard deviation on COST3 (0.46) shows that the position on low-cost VR is shared across roles, study levels, and fields of teaching.

This finding indicates that the typical implementation pathway proposed in current literature—high-end head-mounted displays such as the HTC Vive, the Meta Quest, or the Microsoft HoloLens [40], [51], [67], [68]—does not match the operational realities of the studied training institutes. In resource-constrained settings, deploying high-end VR would likely create an additional technological divide between institutes.

Therefore, the critical challenge is not the design of a high-fidelity visual experience but the design of a sufficient experience around the devices that the learners already own (smartphones) at a price point compatible with public workshop budgets. This represents a frugal-innovation problem [69]–[72]. Reframing the challenge in these terms shifts the engineering focus: the headset becomes a passive optical component (cardboard, ~US$10), the computing platform becomes the student's own smartphone (BYOD), and the requirement for active network access is addressed by running the evaluation algorithms on-device. This conceptual framework is illustrated in Figure 5.

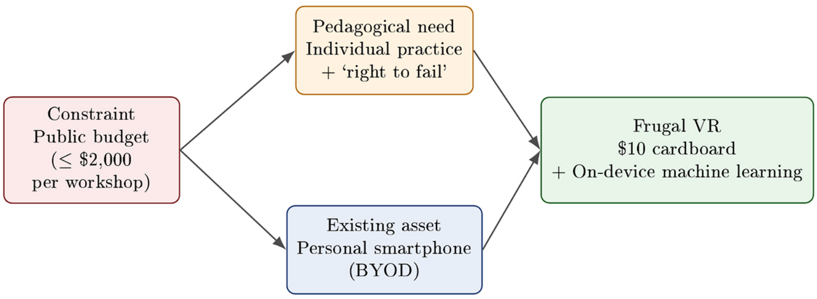

Fig. 5. Frugal-innovation framework derived from the integrated findings

5.4 Future design implications: proposed smartphone-VR and on-device machine learning architecture

The conceptual framework presented in Figure 5 serves to identify what a frugal solution must deliver. To guide future prototyping, we translate these empirical stakeholder findings into a systematic architectural design. Since this system has not yet been physically built or empirically tested for learning outcomes, **the proposed architecture represents a future design implication derived directly from our needs analysis**, rather than a validated result.

Five specific empirical constraints from our sample shape this proposed software architecture:

- **On-device execution:** the high agreement on cost barriers (COST1: M = 4.80; COST3: M = 4.78) and infrastructure concerns suggests that the architecture must run entirely on-device to remain viable without dedicated servers or cloud dependencies.
- **Single-device deployment:** (PEOU1: M = 4.75) and BYOD preferences indicate that user interaction should be optimized for simple gaze-and-tap interfaces, which are compatible with basic, passive cardboard headsets.
- **Mistake-tolerant procedural loops:** the priority placed on a safe environment (PU2: M = 4.68; EQ2: M = 4.55) requires the application logic to support an active procedure execution engine that allows standard operating procedures to be repeatedly attempted, failed, and corrected.
- **Offline-first persistence:** the larger variance in BI (BI1: M = 4.42, SD = 0.73) indicates varying personal study contexts, suggesting that core features should operate offline without requiring continuous network connectivity.

- **Zero local-server footprint:** to address teachers' workshop-level budget limitations and administrative delays, the design eliminates the need for per-institute server infrastructure by hosting all database models and 3D assets on the mobile device.

The UML component diagram in Figure 6 conceptually organizes these constraints into a four-layered future design architecture. The **Presentation** layer is designed around stereoscopic rendering and gaze-and-tap interaction models. The **Application logic** layer manages the pedagogical execution (Procedure Engine, Session Manager, and Feedback Module). The **Intelligence** layer is designed to host a light, on-device machine learning stack (including a gesture classifier and sequence evaluator running on TFLite Micro) to process basic device IMU sensor inputs. The **Persistence** layer operates locally, utilizing a lightweight SQLite database and compressed 3D assets.

By detailing this architecture, we establish a concrete, testable blueprint that links stakeholder-informed requirements directly to software components. This provides the technical framework for subsequent empirical validation of actual learning outcomes, task performance, and system latency in a future experimental study.

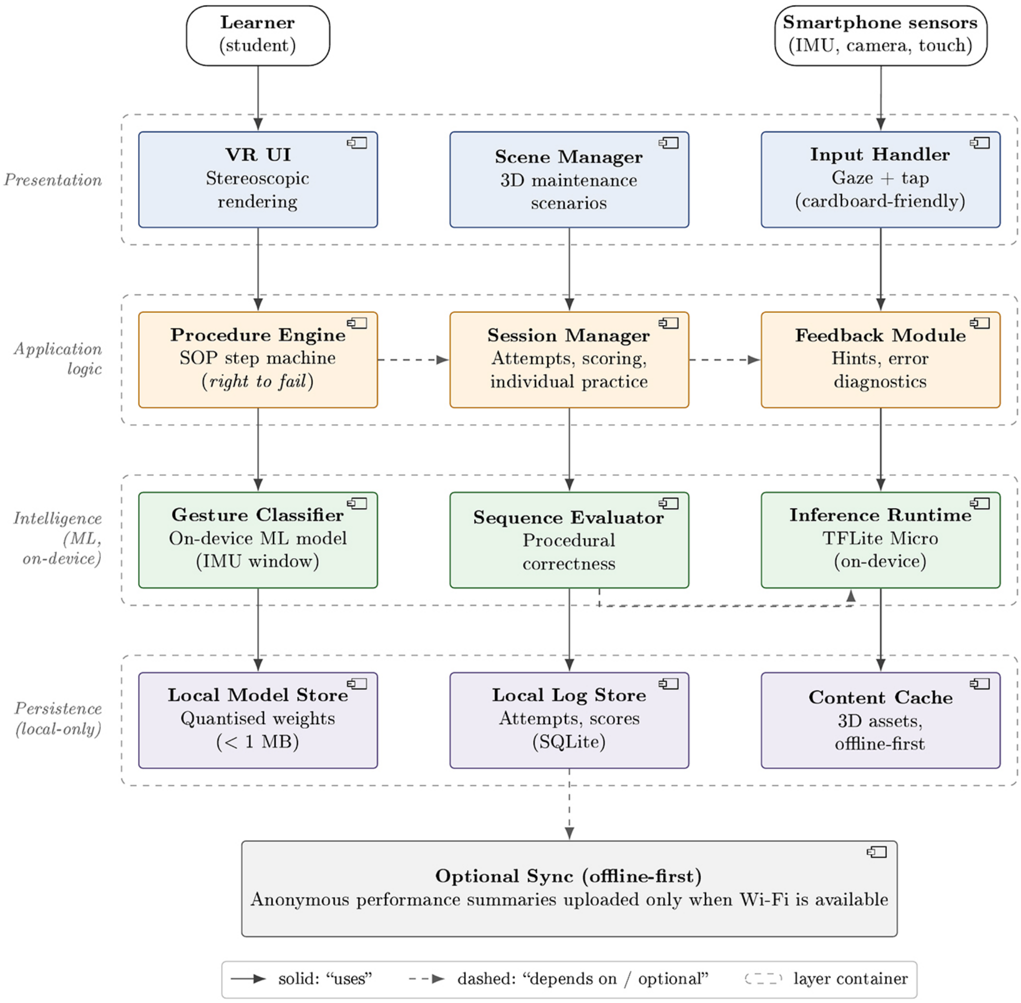

Fig. 6. UML component diagram of the proposed smartphone-VR application for Maintenance 4.0 training

Notes: The architecture represents a future design implication derived from the integrated needs analysis: a Bring-Your-Own-Device front-end addresses COST3 (M = 4.78); an on-device machine learning layer aims to address COST1 (M = 4.80) and infrastructure concerns; and a local-first persistence layer is structured to support unlimited individual practice and the right to fail (PU2: M = 4.68; EQ2: M = 4.55) without direct cloud requirements.

5.5 Limitations

Three limitations of the present work should be noted. First, the study reports PU and BIs rather than direct measures of educational impact, knowledge retention, or skills transfer. While the TAM model provides a structured framework for understanding stakeholder expectations, the actual educational effectiveness of a low-cost smartphone-based VR solution remains to be established through controlled empirical testing. Second, the quantitative sample is dominated by students (170 of 260), which mirrors the population of public training institutes but means that teachers and industry managers carry a smaller statistical weight in the descriptive results; the qualitative phase partially balances this by giving each profile a comparable number of voices. Third, the participants are drawn from public institutes operating under similar budget constraints; external validity to private and well-funded institutes remains to be evaluated.

6 CONCLUSION AND FUTURE WORK

This paper has presented an exploratory sequential mixed-methods needs analysis and technology acceptance study regarding Maintenance 4.0 training under severe budget constraints, utilizing 35 semi-structured interviews and a 260-respondent TAM-informed survey. The findings indicate that physical equipment shortage is perceived as a primary pedagogical barrier and that low-cost, smartphone-based VR is perceived as a realistic and sustainable alternative by the surveyed students, teachers, and industry professionals.

Rather than demonstrating the learning effectiveness of VR, the contribution of this work is foundational: it provides a systematically documented set of stakeholder requirements and maps them to a candidate, on-device mobile software architecture. By reframing the problem around frugal-innovation constraints, we establish a conceptual design that addresses cost without introducing heavy infrastructure requirements.

The subsequent phase of this study will focus on the prototyping and empirical evaluation of this smartphone-based VR application with a US$10 cardboard headset. We plan to conduct comparative experimental testing to measure direct learning outcomes, procedural retention, and motor skills transfer, evaluating whether this frugal VR design can deliver perceived educational utility comparable to high-end VR setups.

7 DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the author(s) used Claude AI to improve formatting and language. After using this tool/service, the author(s) review(s) and edit(e) the content as needed and take(s) full responsibility for the content of the publication. All references, quotations, numerical values, and methodological descriptions have been manually verified by the authors.

8 ACKNOWLEDGMENTS

8.1 Funding

This study was supported by the CNRST (National Center for Scientific and Technical Research) through the "PhD-Associate Scholarship – PASS" Program.

8.2 Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

8.3 Ethical statement

No formal written ethics waiver was issued. The determination that formal approval was not required was made by the authors in consultation with the relevant department heads, in accordance with institutional guidance for minimal-risk anonymous educational research. Informed consent was obtained from all individual participants included in the study, and all data were anonymized and stored securely.

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