Pedagogical Framework for Immersive Digital Twins

Written by: dr. Cristina Obae &
Anny Nusrat, NEdHo
Publication date: 30/04/2026
Last updated: 02/07/2026

Co-funded by
the European Union

Pedagogical Framework for Immersive Digital Twins

Version 1.5

-Public version-

Co-funded by
the European Union

Table of contents

Co-funded by the European Union

1 Theoretical background

1.1 Immersive Digital Twins (IDTs)

An immersive digital twin (IDT) is generally defined in industry as a high-fidelity, digital twin of a real-world system (object, process, learning environment or even person) that is updated in (near) real-time with data from its physical counterpart and is experienced by learners through immersive technologies (e.g., VR/AR/XR), enabling rich simulation, exploration, interaction and adaptation of learning situations (Pathak & Upadhyay, 2024; Ning et al., 2024). The key characteristics of an IDT include: (1) *digital representation* of the real entity; (2) *bidirectional or at least continuous data flow* between the physical entity and its twin; (3) *immersive interface* for learners to interact with the twin; and (4) *pedagogical alignment* if the twin is designed for learning outcomes rather than simply visualization (Pathak & Upadhyay, 2024; Ning et al., 2024). IDTs combine the conceptual rigour of the digital twin paradigm (widely used in industry) with the learning-centred affordances of immersive technologies, thereby supporting experiential, situated, and active learning in higher-education settings.

In the higher-education and VET context (to which IDT4EU project subscribes), IDTs allow students and instructors to engage with a virtual replica of a real system or environment in a secure, flexible setting, where data-driven, scenario-based learning can take place (Daineko, 2025; Ning et al., 2024). Nevertheless, in this particular situation, the bidirectional continuous data flow between the physical and virtual machines (feature 2) is very difficult, if not impossible to maintain. So, **IDTs within IDT4EU are understood as high-fidelity, virtual, interactive models of real-world systems that are experienced by learners through immersive technologies, enabling rich simulation, exploration, interaction and adaptation of learning situations.**

In higher education, immersive digital twins (IDTs) function as distinct learning environments. They integrate three key characteristics: (1) high fidelity, (2) immersion, and (3) interactivity.

Together, these features allow students to engage with systems in ways that closely replicate real-world professional practice.

However, IDT-based learning environments do not simply replace physical settings; they extend and intertwine physical and virtual spaces into a unified learning context. As a result, designing learning scenarios for and teaching in such environments requires knowledge and competencies that go beyond those needed in traditional classrooms. To account for this expanded complexity, the extended TPACK-XD framework (Obae, 2026; Obae et al., 2025), which was specifically developed for hybrid physical–virtual learning environments, provides a necessary lens for understanding and supporting the effective use of IDTs in higher education.

1.2 TPACK-XD

TPACK-XD is an adaptation of the TPACK framework (Mishra & Koehler, 2006; Koehler et al., 2014; Mishra, 2019; Brianza, 2022; Brianza et al., 2024) for Higher Education Institutions (HEI) immersive learning environments. As illustrated in Figure 1, TPACK-XD includes besides the traditional technological (TK), pedagogical (PK), content (CK) and context (XK) knowledge, two more domains that are essential for planning and teaching courses in immersive learning environments: design (DK) and learner (AK) knowledge.

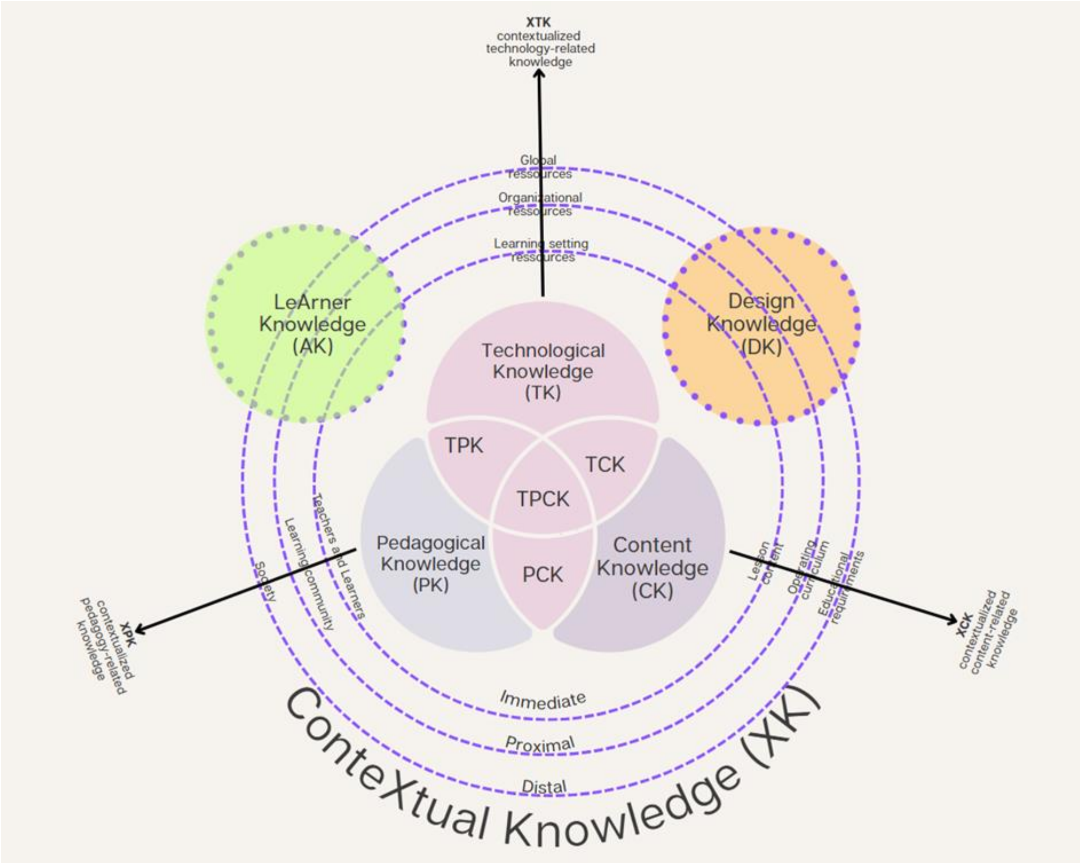


Figure 1. TPACK-XD framework (Obae, in press)

Within TPACK-XD all knowledge domains are interconnected. Such a complex set of knowledge cannot be detained by only one individual, so, in order to efficiently plan and implement learning experiences in an IDT-based learning environment, a team of experts is needed. The teacher/instructor remains a key person of this team, and thus, pedagogical knowledge (PK) is central to TPACK-XD.

1.3 Pedagogical Knowledge Domain

Pedagogical Knowledge (PK) in higher education or VET refers to the **professional knowledge instructors hold about how teaching and learning work, independent of any specific subject area.** It supposes that the teacher understands instructional strategies, classroom facilitation, assessment principles, feedback practices, learning theories, and principles for managing learning environments (Shulman, 1986; Biggs & Tang, 2011). All of them are reflected in the learning scenarios (Cuvelier et al., 2025). So, analysing how the teacher designs and delivers a learning scenario can provide solid insights into the elements of PK necessary for IDTs.

Within PK, researchers distinguish **General Pedagogical Knowledge,** which is in fact the knowledge of overarching teaching principles such as active learning, scaffolding, motivation, learner engagement, assessment for learning, and classroom management. In higher education, general pedagogical knowledge represents a foundational domain applicable across disciplines and is increasingly linked to the professionalisation of university teaching (Ramsden, 2003; Prosser & Trigwell, 1999). The literature also highlights existence of the **Pedagogical Content Knowledge** (OECD, 2021; Dickerson, 2022), which finds itself at the intersection between PK and content knowledge (CK).

Content knowledge (CK) refers to the teacher's deep understanding of the concepts, structures, methods of inquiry, and epistemological foundations of a discipline. It includes knowing **what** is taught, like facts, theories, models, and ways of thinking that define a field (Shulman, 1986). CK is essential but insufficient on its own for effective teaching: instructors also need **pedagogical knowledge (PK)**, which concerns **how** to teach: designing learning activities, facilitating understanding, managing learning environments, and assessing learning. Shulman (1987) argues that high-quality teaching arises when CK and PK interact, forming pedagogical content knowledge (PCK), which enables teachers to transform disciplinary content into teachable and learnable forms. In higher education, CK provides the disciplinary foundation, while PK provides the repertoire of strategies needed to make that content accessible, meaningful, and aligned with learners' needs.

Alongside PK and CK, there is also **Learner Knowledge (AK)**, which is involved in the teaching process. All three of them constitute distinct but interconnected domains: if CK refers to mastery of disciplinary concepts, structures, and ways of thinking, PK to how to teach effectively, AK is the knowledge of learners and their characteristics. It is thus referring to understanding students' prior knowledge, misconceptions, motivational patterns, levels of autonomy, cultural and linguistic backgrounds, and learning challenges (Shulman, 1987; Jarni, 2024). Empirical studies consistently treat these domains separately, demonstrating that they predict different dimensions of teaching effectiveness (Meij, 2025; Grigaliūnienė et al., 2024).

Co-funded by
the European Union

Their separation allows teachers to adapt pedagogy to the specific learners they teach as **PK provides the "how," CK the "what," and AK the "for whom."**

These domains relate closely to **Context Knowledge (XK)** and **Design Knowledge (DK)**. XK includes institutional, curricular, technological, regulatory, and cultural aspects that influence teaching in higher education, such as class size, assessment regulations, program structures, digital infrastructures, and disciplinary norms (OECD, 2021; Dickerson, 2022). DK refers to the ability to design coherent learning environments, aligning learning outcomes, activities, modalities, resources, technologies, and assessments (Laurillard, 2012). In contemporary higher-education settings, DK integrates PK, CK, AK, and XK to produce evidence-based and learner-centred course designs, particularly in blended, online, and complex multimodal configurations.

Instructors who aim to integrate **immersive digital twins (IDT)** into their courses require not only strong DK and XK but also specific professional skills. Research on technology-enhanced learning emphasises that immersive learning environments demand robust **communication skills** (for briefing, debriefing, guiding students through complex simulations), **risk-management skills** (anticipating ethical, safety, cognitive-load, and data-privacy risks), and **collaboration skills** (working with IT teams, instructional designers, domain specialists, and sometimes industry partners) (Ciriza-Mendívil et al., 2022; Lu, 2024). These skills complement PK, CK, and AK, enabling instructors to design safe, pedagogically aligned, and contextually appropriate learning experiences that rely on the affordances of IDTs.

Co-funded by
the European Union

2 Research method

The research method to be used for defining the IDT4EU pedagogical framework is Design-Based Research (DBR) which supposes co-creating with participants at the research and having multiple iterations of design cycles to define the final product: 1. definition of Pedagogical Knowledge, 2. testing of pedagogical theories and approaches that are best-adapted to be implemented in an IDT learning environment, and 3. creation of the IDT4EU pedagogical final framework.

The DBR will take place between January 2026 – August 2028 and will be divided into three phases (see Annex 1) guided by the research question **RQ: What framework and guiding principles can support the selection of pedagogical approaches for effective[1] implementation of immersive digital technologies (IDTs) in higher education?**

Phase 1: Research interviews with the teachers and students of the IDT4EU partner universities are to be conducted online with MS Teams and transcribed. They will be further stored and analysed by the researchers involved in the IDT4EU project. A short report summarising the qualitative findings based on these interviews will be published and the link will be shared with the participants. The research questions related to this phase are:

- RQ1: What is Pedagogical Knowledge?
- RQ2: Which pedagogical theories and approaches are best-adapted to be implemented in an IDT learning environment?
- RQ3: What are the characteristics of the context, learners, and teachers' pedagogical philosophies across the IDT implementations?

Phase 2: Teachers and students from the IDT4EU partner university who volunteer will co-participate in the research. The researchers develop a theoretical framework (Co-design → Construction → Implementation → Data gathering → Evaluation → Reflection) and conduct

[1] In the context of IDT4EU, effective implementation refers to the successful pedagogical integration of Immersive Digital Twins into teaching and learning. It encompasses the design of pedagogically aligned, usable, and contextually appropriate learning environments that support meaningful learning, learner engagement, and practical adoption by educators.

pilot testing, validating intermediate versions of the framework. The preliminary results will be presented at scientific conferences. The research questions for this phase will be:

- RQ4: How can pedagogical approaches be selected and adapted to different IDT implementation contexts?
- RQ5: What characteristics make a pedagogical approach effective in an IDT environment?
- RQ6: How can the effectiveness of pedagogical approaches be evaluated iteratively within IDT4EU implementations?

Phase 3: The researchers analyse the data gathered during Phase 2, further conceptualise the pedagogical knowledge elements, and finalise the framework and guiding principles that can support the selection of pedagogical approaches for effective implementation of IDTs in higher education. A scientific article will be written by the researchers. Once published, the link to the article will be shared with the participants in the DBR research, the IDT4EU website and social media. The research questions will be:

- RQ7: Which pedagogical knowledge elements are most critical to effective IDT implementation across diverse contexts?
- RQ8: Which factors influence the effectiveness and sustainability of IDT pedagogical approaches?
- RQ9: Which design principles can guide teachers in selecting and adapting pedagogical approaches for IDT implementation?

The evaluation of the IDT4EU pedagogical framework follows an iterative approach consisting of three complementary evaluation cycles (see figure 2). The first cycle evaluates the quality of the framework itself by examining its clarity, completeness, and practicality. The second cycle assesses how effectively the framework supports educators in designing and implementing high-quality IDT-based learning environments. The third cycle examines the impact of using the framework on teaching and learning, including learner outcomes, engagement, and educator experience. Evidence gathered across the three cycles informs successive refinements of the framework, supporting its continuous improvement through iterative DBR implementation.

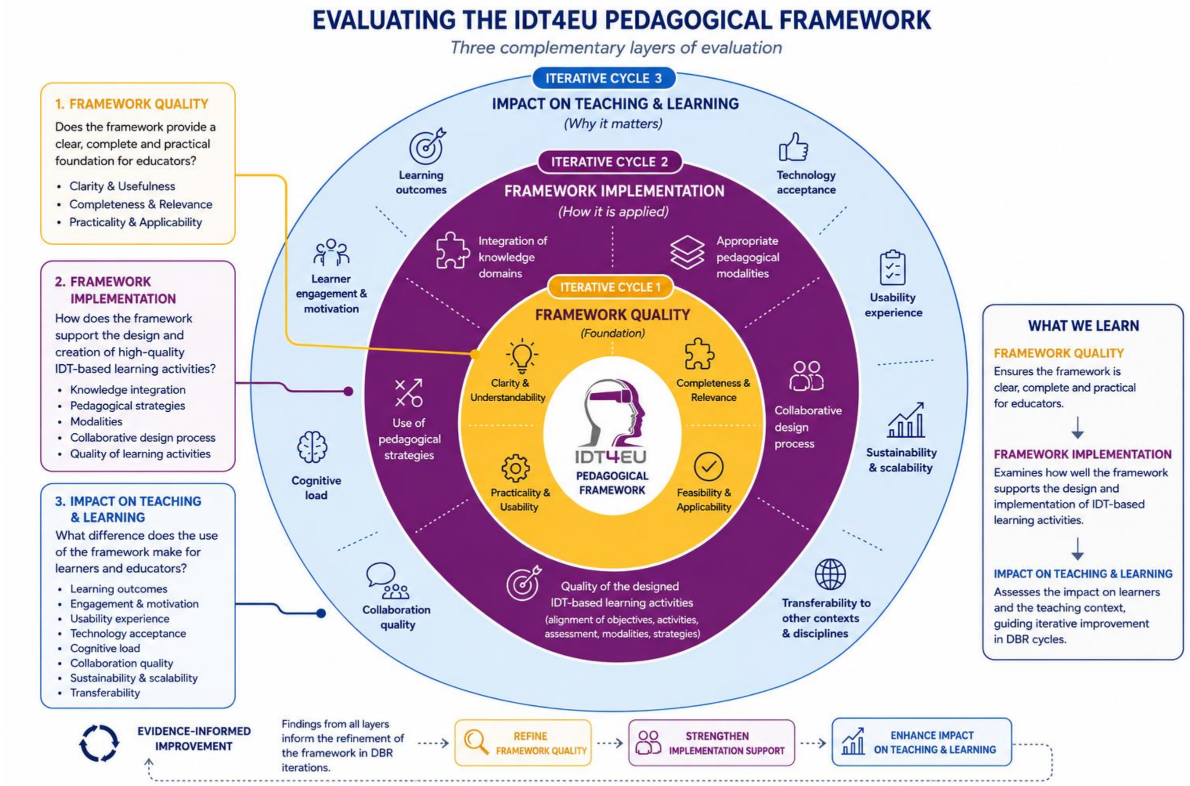


Figure 2. Iterative evaluation model of the IDT4EU pedagogical framework

Special attention will be given to data protection and ethical handling of research data throughout the study. All personal data collected during the research will be treated in a pseudonymised form, encrypted, and securely stored for the duration of the project. Access to the data will be restricted to authorised researchers involved in the IDT4EU project as detailed in the Data Management Plan. Upon completion of the research period, all collected data will be fully anonymised to ensure participant confidentiality and to support the reliability and integrity of the research outcomes. The anonymised dataset will then be archived on encrypted physical storage. In addition, all research data stored on SharePoint Online will be permanently deleted after August 2028, in accordance with the project's data management and retention policies.

3 Phase 1 Research data

All empirical data were collected through semi-structured, in-depth interviews. A total of 20 interviews were conducted across partner institutions in France, Italy, and Poland, comprising 11 teachers and 9 students as illustrated in the Table 1 below. Among the teachers, two participants were from France, two from Italy, and seven from Poland. The student sample was evenly distributed, with three participants from each country.

Participants were recruited through purposive sampling to ensure representation of teachers and students from the three IDT4EU partner institutions involved in the pilot implementations. Data collection continued until thematic saturation was reached, with no substantially new themes emerging from the final interviews. The number of 20 interviews was considered sufficient for this phase of the Design-Based Research process, as the aim was to obtain rich qualitative insights to inform the iterative development and refinement of the pedagogical framework rather than achieve statistical generalization.

Number	Code	Universit	Role	Interview Language	Interview lenght	Observations
1	T1	ENSAM	Teacher	French	46:17:00	
2	T2	ENSAM	Teacher	English	43:25:00	
3	T3	POLIMI	Teacher	English	57:31:00	
4	T4	POLIMI	Teacher	English	41:03:00	
5	T5	WUT	Teacher	English	60:00:16	
6	T6	WUT	Teacher	English	60:02:46	
7	T7	WUT	Teacher	English	42:55:00	
8	T8	WUT	Teacher	English	46:07:00	
9	T9	WUT	Teacher	English	52:17:00	
10	T10	WUT	Teacher	English	41:06:00	
11	T11	WUT	Teacher	English	52:08:00	
12	S1	ENSAM	Student	English	18:14:00	
13	S2	ENSAM	Student	English	17:53:00	
14	S3	ENSAM	Student	English	27:34:00	
15	S4	POLIMI	Student	English	20:15:00	French exchange student
16	S5	POLIMI	Student	English	12:06:00	
17	S6	POLIMI	Student	English	15:22:00	
18	S7	WUT	Student	English	19:00:00	
19	S8	WUT	Student	English	19:56:00	
20	S9	WUT	Student	English	12:55:00	

Table 1. Interviews mapping (Source: own elaboration)

Interview duration varied by participant group: teacher interviews lasted 41-60 minutes, while student interviews ranged from 12 to 27 minutes. The teacher interviews addressed the full spectrum of knowledge domains under investigation, whereas student interviews focused specifically on learner knowledge (AK).

All interviews were conducted and transcribed using Microsoft Teams. Transcripts were subsequently reviewed and manually corrected to address transcription errors and ensure clarity and accuracy. One interview was conducted in French and translated into English; all remaining interviews were conducted in English.

4 Phase 1 Data Analysis

The analysis followed a structured, multi-stage qualitative procedure supported by ATLAS.ti. A dedicated project ("IDT4EU") was created, into which all 20 interview transcripts were imported. A hybrid coding approach was adopted, combining inductive and deductive strategies (see Figure 3). In the initial stage, open coding (inductive) was conducted across all transcripts, resulting in an initial set of 211 codes (see examples in Annex 2). Coding proceeded iteratively until thematic saturation was reached. Through repeated review and refinement, the coding scheme was consolidated to a final set of 208 codes.

Subsequently, a deductive phase was applied, aligning the codes with the research questions and the TPACK-XD framework. Codes were grouped into 29 code groups (categories) within ATLAS.ti, reflecting key dimensions of the analytical framework. Particular attention was given to pedagogical knowledge (PK), while also allowing for the identification of emergent codes extending beyond the predefined TPACK-XD domains.

In the final stage, categories were further synthesised into higher-order themes, resulting in five overarching themes that structure the findings presented in Section 5. These themes informed the progression from codes → categories → design principles, ensuring a clear analytical link between empirical data and the resulting pedagogical framework.

Overall, the analytical process can be summarised as follows: initial coding alignment with TPACK-XD domains (with emphasis on PK) → identification of emergent codes → aggregation into categories → abstraction into themes → derivation of design principles and IDT4EU pedagogical framework.

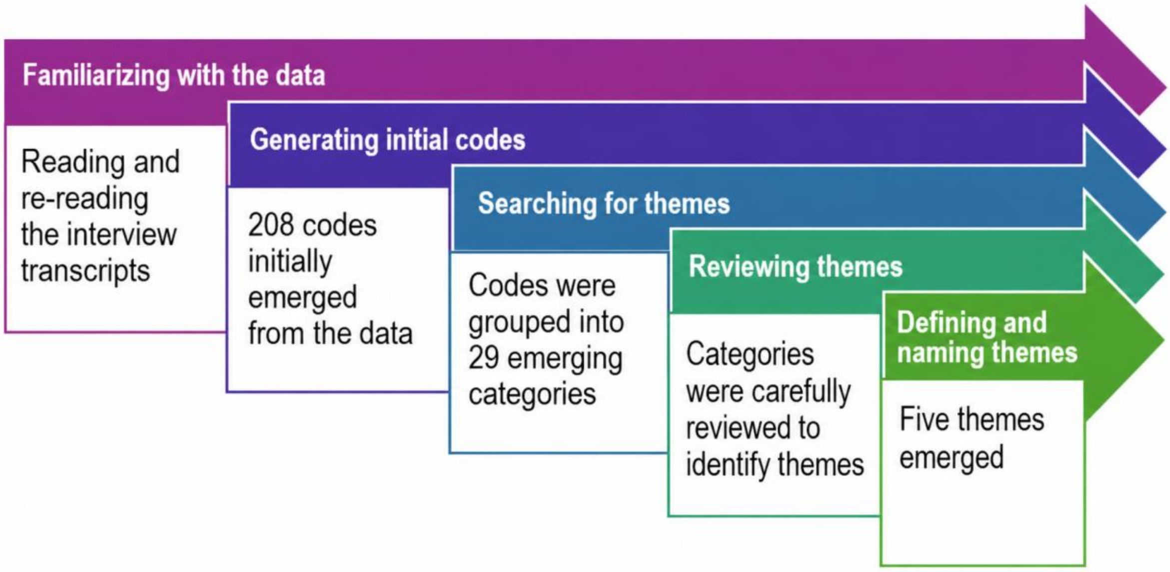


Figure 3. The analytical steps and their sequencing were adapted from the thematic analysis framework proposed by Braun and Clarke (2006). All identified themes, categories, and key codes are presented in Annex 2.

5 Phase 1 Findings

This section presents the findings from the interview data, analysed through a thematic content analysis.

5.1 Core theories

Although interview questions did not explicitly address learning theories, participants' descriptions of their teaching practices suggest alignment with constructivist and experiential theoretical approaches as core pedagogical foundation. Constructivism theory postulates that students learn best when they are actively involved in the learning process, rather than just listening to explanations. Learning happens when students connect new information to what they already know, discuss ideas with others, and make sense of things through their own thinking. In this approach, the teacher's role is not only to explain content, but to guide,

Co-funded by the European Union

support, and create opportunities for students to explore and understand. Experiential learning, on the other hand, refers to learning through direct experience, where learners actively engage in realistic situations, reflect on what they do, and use that experience to build understanding. Its core idea is that learning becomes deeper and more durable when learners “do” rather than only “listen.”

Teachers frequently emphasised interaction, questioning, discussion, and encouraging students to reflect on their understanding. Several participants described prompting students to explain unexpected results or engage in deeper reasoning, indicating a shift beyond transmission-based teaching. All these directly connect to constructivist principles.

In addition, both teachers and students highlighted the importance of learning through experience. Those with prior exposure to IDTs described these environments as enabling learners to actively engage with realistic situations. Students are placed “inside” the learning process, rather than observing it, which contributes to more memorable and meaningful learning. A recurring theme was the value of safe experimentation. Participants noted that IDTs allow learners to test ideas, make mistakes, and explore outcomes without real-world consequences. This creates a space for trial-and-error learning that would be difficult to achieve in physical environments.

Overall, the findings suggest that teachers are already implementing practices aligned with active, experience-based learning, even if these are not explicitly framed using formal pedagogical terminology.

5.2 Pedagogical modalities

Analysis of the interviews data on IDT use shows that learning typically happens in three main ways that will be further identified as “pedagogical modalities”. According to the participants, these are: immersive learning (students are fully engaged in a virtual or simulated environment), hybrid learning (a mix of digital and face-to-face activities), and differentiated learning (adapting tasks and support to meet different student needs).

Immersive modality refers to a way of learning where students are fully engaged in a simulated or virtual environment (such as VR or 3D spaces). In this modality, learners are placed “inside” the experience, allowing them to explore, interact, and learn by doing in a realistic and interactive setting. Both teachers and students expressed generally positive views about immersive learning. Most participants had encountered immersive technologies outside formal education, for example in industry settings, study visits, or as part of research projects. Only one participant reported having no prior experience or knowledge of such tools. Overall, participants considered immersive technologies beneficial for learning. As one student noted, “I can memorize better with immersive technology, always.” Several participants highlighted specific advantages. Some emphasised that IDTs support experiential learning, allowing students to learn by doing. Others pointed out that these technologies reduce geographical barriers, enabling access to places and situations that would otherwise be difficult to reach. A few participants also stressed the value of safe experimentation. As one teacher explained, immersive environments allow learners to practise without the risk of damaging equipment or causing harm.

At the same time, participants reported some challenges related to physical comfort. Five individuals mentioned experiencing issues such as dizziness, nausea, headaches, or eye strain. For example, one participant described feeling comfortable at first, but becoming disoriented after about 15 minutes of use.

Overall, the findings suggest that immersive technologies can improve engagement, support safe and practical learning experiences, and expand access beyond physical limitations. However, they also highlight the need to consider potential health and comfort issues when designing and implementing these learning environments.

Hybrid delivery refers to a way of teaching that combines in-person (face-to-face) and online or digital learning. Students learn partly in a physical classroom and partly through virtual or digital environments, allowing flexibility and the use of both types of learning experiences. A key finding of the study is that teachers strongly agree that IDTs should complement, not replace, physical learning. Rather than choosing one over the other, they see the greatest value in combining immersive and real-world environments to enhance the overall learning experience.

Teachers explained that immersive environments make it possible to show and explore things that are not accessible in physical settings, for example, seeing inside machines, visualising manufacturing processes, or practising without risk. At the same time, physical workshops remain essential for hands-on experience. As one teacher noted, the real benefit comes from using both environments together, as each offers different advantages. This perspective aligns with a blended (or hybrid) learning approach, where digital and face-to-face experiences are intentionally combined to support learning more effectively.

Differentiation refers to adapting teaching to meet the different needs, abilities, and learning styles of students. This can include varying the pace of instruction, the type of tasks, the level of support, or the way students demonstrate their learning, so that all learners can progress effectively.

Teachers reported using a range of strategies to address differences between learners. Most explained that they begin by identifying students' needs, abilities, and expectations at the start of a course, and then adapt their teaching accordingly. In practice, this includes progressing step by step, explaining concepts at a slower pace when needed, including breaks during sessions, providing specific support for students with special needs, and organising mixed-ability groups so students can learn from each other.

One teacher described this approach as trying to create a learning process that works for everyone, while still adapting activities based on individual goals and skill levels.

However, not all teachers reported using differentiated strategies. A small number indicated that they do not adapt their teaching to different learner needs and instead use the same approach for all students.

5.3 Pedagogical strategies

Pedagogical strategies are the different methods and approaches teachers use to help students learn effectively. They include how lessons are organised, how students are engaged (e.g., through discussion, group work, or projects), and how understanding is supported and assessed. In simple terms, teaching strategies are the practical ways teachers turn learning goals into classroom activities. Analysis of the data identified five main pedagogical strategies used or preferred by participants: active learning, collaborative learning, project-based learning, gamification, and feedback & assessment. Although most teachers did not refer to these strategies using formal pedagogical terms, they were able to clearly describe how they teach in practice. This indicates that they are already applying these approaches in their teaching, even if they are not naming them explicitly.

Active learning is a teaching strategy where students are directly involved in the learning process through activities such as discussion, problem-solving, or hands-on tasks rather than just listening to explanations. Both teachers and students interviewed preferred active learning because it makes learning interesting and enjoyable rather than a one-way process of knowledge transmission. Both teachers and students, in fact, advocated for IDT-based learning as it promotes active learning by engaging learners into real life related experiences: "…the main point of the use of immersive technology is the active learning. The active engagement, because to get onward, to make progress, the person that used the technology should be involved." (S4) In most of the cases participants of this study preferred a lecture followed by some active participation.

Collaborative learning is a teaching strategy where students work together in pairs or groups to solve problems, share ideas, and learn from each other. Collaborative learning was identified as another commonly used teaching strategy. Several teachers reported using group work not only to support learning, but also as a way to address differences between students, allowing them to learn from each other. One educator noted that this type of collaboration works well even in immersive environments. Teachers and students alike viewed collaboration as a central element of effective IDT-based learning, although teachers primarily discussed collaboration as an instructional strategy, whereas students emphasised peer interaction during learning activities. For example, one teacher explained that students present their work not only to the teacher, but also to their peers, creating opportunities for discussion and exchange between groups. In addition, one participant highlighted that collaboration is important not only for students, but also among teachers. Moreover, working together as educators is seen as essential for designing and implementing effective immersive learning environments.

Project-based learning is a teaching strategy and method where students learn by working on real-world problems or projects over a period of time. Instead of only studying theory, students actively explore, create, and apply knowledge to complete a meaningful task. Project-based learning emerged as another widely used teaching strategy, highly appreciated also by students. This approach is particularly well suited to IDT environments because it allows students to engage in realistic, and meaningful hands-on experiences. Some teachers are already using it in their courses. Students also recognise its value. As one student explained, group projects can sometimes feel "more demanding than preparing for exams", but they lead to a different and often deeper kind of learning. They also provide opportunities to exchange ideas with peers and develop teamwork skills.

Another pedagogical strategy preferred by both teachers and students is **game-based or gamified learning.** This approach involves using elements from games, such as challenges, levels, points, or competition, to support learning. The aim is to make learning more engaging and motivating, while still focusing on clear learning objectives.

Participants identified this as both a strategy they already use and one they would like to use more often. It is particularly effective in immersive environments, where students can feel fully involved in the experience. Interviewed teachers noted that this approach increases engagement, encourages participation, and supports gradual progress. As one participant explained, immersive environments can create a strong "wow" effect, where students feel like they are playing rather than working. This initial sense of enjoyment helps capture their attention and motivates them to continue. Once students are engaged, teachers can then guide them toward deeper learning and specific learning goals.

Feedback and assessment were also identified as essential parts of effective teaching and learning. Using this strategy involves regularly checking students' understanding and providing feedback to help them improve. It also includes gathering feedback from students to adjust teaching when needed. Participants highlighted that assessment can increase student engagement. For example, one student explained that knowing they will be assessed motivates them to stay focused. Teachers also emphasised the importance of receiving feedback from students to improve their own teaching.

In practice, teachers use a variety of methods. Some design short assessments at the end of each class to check understanding, while others use interactive tools such as Kahoot. These tools are popular because they create a game-like experience, making assessment more engaging for students.

5.4 TPACK-XD domains

Data analysis also identified participants' current position upon the six domains of TPACK-XD revealing different levels of awareness and development across the sample.

The data indicate varying levels of **technological knowledge** among the teacher participants. Six participants described themselves as confident and comfortable users of technology, whereas one reported limited confidence in this area. At the same time, eight teachers emphasised that understanding and using technology constitutes an essential competency for contemporary teaching. All participants expressed a generally positive attitude towards the use of IDTs in education. Two teachers reported prior experience with IDTs at a small-scale, in a research project, while three indicated that they are currently integrating immersive technologies, virtual environments, and simulations into their teaching practice.

Content knowledge was consistently identified by all teacher participants as a critical component of effective teaching. Participants reported regularly updating their subject knowledge through recent publications, reference materials, online sources, and, in some cases, AI-supported tools. There was strong consensus regarding the central role of content knowledge in shaping teaching quality and effectiveness. As one participant emphasised: "My subject knowledge has, I would say, 10 out of 10—the highest impact on teaching. Because if you have no knowledge, then your impact will be low. You can't mislead your students into thinking that you know." (T11)

Learner knowledge emerged as an important category in the analysis of the interview data. Eight teacher participants reported actively seeking to identify learners' characteristics (such as prior knowledge, background, and learning needs) particularly at the beginning of a course. This is typically achieved through a range of activities, including discussions, questioning, quizzes, game-based tasks, and observation. Based on this initial understanding, teachers reported adapting course design and planning targeted support to enhance learning experiences. To further support students, participants indicated that they provide additional guidance through consultations, both during and outside scheduled class time, to address specific learning challenges. While teachers described how they identify learner characteristics and adapt instruction accordingly, students provided complementary evidence by describing the types of learning experiences they found engaging, authentic, and supportive.

Contextual factors, particularly institutional resources and administrative structures, were reported to influence teaching practices in several cases, especially with regard to the implementation of advanced technologies such as IDTs. As one participant noted, the development of digital twin environments requires sustained financial investment, which may limit the continuity of such initiatives. Six teachers highlighted challenges related to insufficient infrastructural support within their institutions. Additionally, some participants indicated that introducing innovative practices may require prior approval from institutional authorities, and that pedagogical choices are, at times, shaped by institutional regulations. One participant also pointed to the significant influence of national accreditation bodies on teaching and learning practices. At the same time, perspectives varied across the sample. Six participants reported being able to teach with limited influence from institutional constraints, while four suggested that their teaching practices are largely independent of broader national, social, or cultural contexts. These findings indicate a heterogeneous perception of contextual influence across participants.

Finally, teachers identified several key factors that inform their course creation process and are thus part of the **design knowledge**. These include consideration of learners' future career needs, alignment with intended learning outcomes, integration of up-to-date disciplinary developments, incorporation of interactive learning activities and relevant examples, as well as the selection of appropriate tools and technologies for course delivery. Regarding lesson design, participants generally described a structured progression from foundational to more advanced content, often combining lectures with practical activities, as one participant explained: "…we always start with clarifying terminologies and theoretical foundations, and then move towards more practical examples, test activities, and group work. Sometimes students work in groups and present their own perspectives…" (T3). This excerpt illustrates how design knowledge is operationalised through the deliberate structuring of learning sequences, integrating theory, practice, and interaction into a coherent learning experience.

5.5 Cross-cutting competencies

Beyond the core TPACK-XD domains, the analysis also points to the emergence of three cross-cutting competences: communication, collaboration, and risk management.

Effective **communication and collaboration** among educators, technical developers, institutional stakeholders, and learners emerged as key enablers for the successful implementation of IDTs in teaching and learning contexts. As illustrated by one participant: "We brought together several colleagues who teach deformation in forging and colleagues from secondary schools. And when we started to see the machines moving and everything, we said: what scenario could we imagine?" (T1) This example highlights the importance of structured, interdisciplinary collaboration in the co-design process. Such coordinated interaction is a critical prerequisite for developing immersive learning environments that are both pedagogically coherent and technically feasible.

The analysis identified three main **risk management** dimensions associated with the implementation of IDTs: technical, financial, and inclusion-related risks. Technical risks relate to system complexity, uncertainty in design and operation, and the need for ongoing technical support.

As one participant with prior experience in IDT implementation explained: "We have to imagine everything the student is going to propose and then set all the parameters… If we didn't anticipate certain actions at the outset, then the system won't produce results, because the network hasn't learned them." (T1) This highlights the challenge of anticipating a wide range of learner interactions when designing IDT environments. In addition, several students reported requiring technical support during use, noting that limited prior experience with such tools can make it difficult to follow instructions effectively.

Financial constraints also emerged as a significant risk factor. As one participant noted: "…if I don't have anyone to help me develop it because I don't have the money to pay them, I won't get any further… and I won't be able to scale it." (T1) This suggests that the development and scalability of IDTs are closely tied to the availability of resources and institutional investment. Finally, issues related to accessibility and inclusion were raised by participants, who pointed out that these technologies are not yet equally accessible to all learners, representing a potential barrier to equitable implementation.

Overall, these findings indicate that the successful integration of IDTs in educational contexts requires careful anticipation and management of technical, financial, and inclusion-related risks through strategic planning and support mechanisms.

5.6 Pedagogical Knowledge as seen by practitioners

Teacher participants in the research interviews generally demonstrated strong content knowledge, but awareness and mostly articulation of PK appeared limited. When invited to define PK, only four participants were able to provide a definition. While these responses were not always conceptually structured, they reflected a partial understanding of the concept. The remaining participants either struggled to define PK or did not demonstrate a clear understanding, even when the concept was rephrased.

Variations were observed across institutions. Among the two teachers from ENSAM, one was unable to define PK even after clarification, while the other provided a brief definition. None of the participants from POLIMI were able to articulate a definition. In contrast, three out of seven teachers from WUT provided definitions, with three participants overall demonstrating sufficient familiarity to respond without additional prompting. One WUT participant appeared conceptually aware of PK but was unable to formulate a coherent definition. In several instances, responses to the question were limited to general evaluative statements (e.g., "it's nice" or "it's very good"), suggesting a lack of conceptual clarity. Overall, these findings indicate that, despite strong disciplinary expertise, pedagogical knowledge remains underdeveloped or insufficiently articulated among a substantial proportion of participants.

5.7 Teacher and Student Perspectives on IDT-Based Learning

Although teachers and students often expressed similar views regarding the pedagogical potential of Immersive Digital Twins, the interviews revealed differences in emphasis that provide complementary insights for the development of the IDT4EU pedagogical framework. Teachers primarily discussed IDTs from a pedagogical design perspective, focusing on curriculum alignment, instructional strategies, assessment, contextual constraints, and the knowledge required to design and facilitate effective learning environments. Their responses frequently highlighted institutional factors, infrastructure, pedagogical planning, and the role of teachers in selecting appropriate learning modalities and strategies.

Students, in contrast, described IDTs primarily through their learning experience. Their responses emphasised learner engagement, realism, motivation, usability, collaboration, opportunities for experimentation, and the perceived value of immersive environments for developing practical skills. Students also identified challenges related to technical usability and physical comfort, including dizziness and eye strain during prolonged use.

Despite these differences in perspective, both participant groups consistently recognised the value of active, collaborative, and experiential learning. Both teachers and students agreed that IDTs should complement rather than replace physical learning environments and highlighted the importance of authentic learning experiences, meaningful interaction, and appropriate pedagogical guidance. These complementary perspectives reinforce the importance of integrating both educator and learner viewpoints during the iterative development of the IDT4EU pedagogical framework.

6 Theoretical Interpretation and IDT4EU Framework

The framework is informed by the complementary perspectives of both teachers and students, ensuring that the resulting pedagogical principles address not only instructional design considerations but also learners' experiences within IDT-based learning environments. Following a DBR logic, this phase moves beyond descriptive analysis to generate both **theoretical** (through the articulation of pedagogical foundations) and **practical contributions** (through the formulation of actionable design principles). The aim is to situate the observed practices within established pedagogical theories and to synthesise them into a coherent framework that can guide the design and implementation of IDT-based learning environments.

The pedagogical knowledge required for teachers who want to use IDT-based learning environments goes beyond what is typically described in the literature. Based on findings from the DBR Phase 1 interviews and the literature review, this knowledge is shaped by other domains (technology, learners, content, context, and design) and can be understood as a system organised into three overlapping layers, as illustrated below. Thus, we can conceptualise pedagogical knowledge for IDTs-based learning environments as an affordance-driven system integrating core learning paradigms, modality configurations, and strategy enactment within a TPACK-XD-informed and collaborative design context.

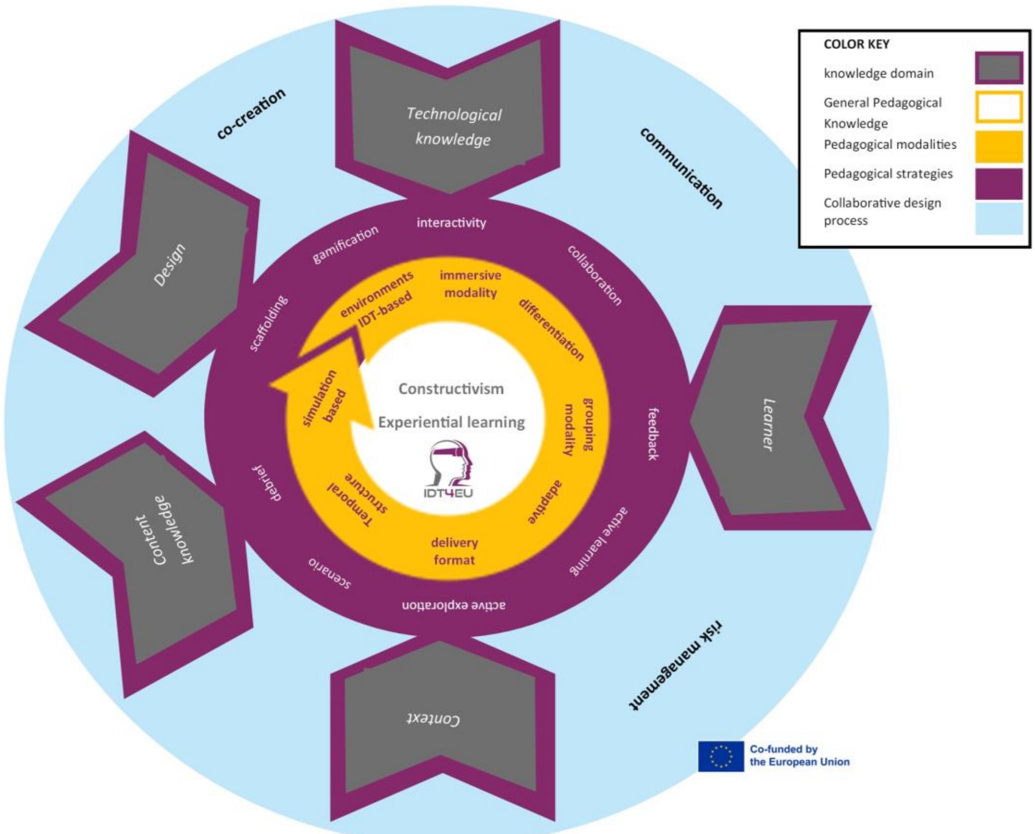


Figure 4. Multi-layered pedagogical framework for IDT-based learning environments (Source: own elaboration)

The proposed framework organises pedagogical knowledge for IDT-based learning environments into three clear and interconnected layers. At the centre (white), it defines the purpose of learning (the "why"), grounded in constructivism and experiential learning as **core theories**, where students learn by actively engaging with and reflecting on realistic situations. The second layer (yellow) represents **pedagogical modalities** (the "where and when"), describing how learning is delivered and structured, including simulation-based or IDT environments, immersive (VR/computer) settings, delivery formats (face-to-face, remote, hybrid), and temporal organisation (e.g., synchronous or asynchronous). The third layer (purple) captures practical **teaching and learning strategies** (the "how"), such as collaboration, feedback, differentiation, gamification, scaffolding, and active exploration, which guide how students interact with the learning environment. Surrounding these layers are key knowledge domains (technological, learners, content, design, and context) that inform all pedagogical decisions. Finally, the entire system is embedded within a collaborative design process involving co-creation, communication, and risk management, highlighting that effective IDT-based teaching requires teamwork across disciplines. Together, the framework shows that teaching with IDTs is not about applying a single method, but about combining the right environment, strategies, and knowledge to create meaningful and effective learning experiences.

6.1 General Pedagogical Knowledge

The general pedagogical knowledge commonly applied in face-to-face learning environments remains relevant in IDT-based contexts. However, when PK interacts with other knowledge domains (technological, learner, content, context, and design) it gives rise to additional, more complex forms of knowledge that teachers need to develop in order to effectively design and implement IDT-based learning experiences (see Section 1.3). Findings from DBR Phase 1 indicate that, in such complex environments, practitioners naturally rely on constructivism and experiential learning as core pedagogical foundations. This limited explicit articulation of pedagogical knowledge, despite the presence of pedagogically sound practices, highlights the need for structured frameworks such as TPACK-XD to support teachers in complex IDT environments.

Experiential learning, as conceptualised by Kolb (1984, 2015), emphasises learning through concrete experience, reflection, conceptualisation, and active experimentation, making it particularly well-suited to simulation-rich and immersive environments such as IDTs. In contrast, **cognitivism** (Piaget, 1970; Bruner, 2009) focuses on internal mental processes, including how learners perceive, process, and organise information. While these approaches differ in emphasis—action and experience versus cognitive structuring—they are not mutually exclusive. In IDT-based learning environments, experiential engagement with simulated systems provides rich input for cognitive processing, supporting the development of deeper understanding and transferable knowledge.

6.2 Pedagogical modalities

Pedagogical modalities refer to the different ways learning is organised and delivered. They describe the type of learning environment and format used, for example: face-to-face, online, immersive (e.g., VR), or a combination of these (hybrid). In simple terms, pedagogical modalities answer the question: where and how does learning take place?

Pedagogical modalities in IDT-based learning environments are represented in the yellow layer of the framework. This includes several interrelated dimensions: the **type of environment** (e.g., simulation-based or IDT environments), the **level of immersion** (e.g., VR-enabled or non-immersive settings), the **delivery format** (face-to-face, remote, or hybrid), the **temporal organisation** (synchronous or asynchronous learning) and **learners' grouping** (e.g. individual, pairs, groups). Together, these modalities define the conditions under which learning occurs and directly influence how learners experience, access, and engage with the content. In IDT contexts, selecting appropriate modalities is a key pedagogical decision, as it determines how effectively the affordances of simulation, immersion, and flexibility are leveraged to support meaningful and context-responsive learning experiences.

6.3 Pedagogical strategies

Pedagogical strategies in IDT-based learning environments refer to the ways in which learning is actively designed and facilitated (how learning takes place), as represented in the purple layer of the framework. This layer includes strategies such as a**ctive and exploratory learning, collaboration, feedback, differentiation, gamification, scaffolding, and scenario-based learning**, which guide how learners interact with the environment, with each other, and with the content. In IDT contexts, scenario-based design plays a central role and can take different forms depending on the level of guidance and flexibility required, including predefined linear scenarios, modular scenarios, or more open, free exploration scenarios (Cuvelier et al., 2025). These strategies are closely linked to the affordances of the technology, particularly interactivity and system manipulation, allowing learners to experiment, make decisions, and learn from consequences in a safe, controlled setting. Teachers must therefore be able to select and combine these strategies to structure meaningful learning experiences, ensuring that student engagement is purposeful and aligned with the intended learning outcomes.

Effective implementation also depends on appropriate classroom facilitation techniques, such as clear briefing before the activity, ongoing guidance during interaction, and structured debriefing after the experience. These techniques help maintain focus, support learner engagement, and ensure that exploration remains aligned with the intended learning objectives. In this context, feedback practices are particularly critical, as they enable learners to reflect on their actions, understand the consequences of their decisions, and consolidate learning. Timely, targeted feedback, whether provided by the teacher, peers, or the system itself, supports deeper understanding and helps transform immersive experiences into meaningful learning outcomes.

Assessment in IDT-based learning environments is closely aligned with clearly defined learning objectives and extends beyond traditional outcome-based evaluation to include the analysis of the learning process itself. Within these environments, students engage with simulation-based tasks to explore concepts, practice skills, and produce learning artefacts that reflect their understanding (Cuvelier et al., 2025). A key advantage of IDTs lies in their ability to automatically capture detailed data on user interactions, including actions, decisions, sequences of behaviour, and response times. This aligns with the growing body of

Co-funded by the European Union

research on learning analytics and process-oriented assessment, which emphasises the value of analysing learner behaviour in digital environments to gain deeper insights into learning (Ifenthaler & Yau, 2020; Siemens & Baker, 2012).

Such data enables a more objective and fine-grained evaluation of learning by moving beyond static assessment products toward continuous, evidence-based monitoring of learner progress. For example, interaction logs can be used to assess problem-solving strategies, decision-making processes, and the development of procedural knowledge within complex systems. This approach is consistent with contemporary perspectives on authentic assessment (Wiggins, 1998), where learners are evaluated through meaningful tasks that mirror real-world practice. In IDT contexts, the integration of automated data capture with pedagogically aligned assessment design allows teachers to better understand not only what students have learned, but also how they learned, thereby supporting more informed feedback, adaptation, and continuous improvement of both teaching and learning processes.

6.4 Principles for IDT design

The Table 2 below synthesises the empirically derived design principles identified through the Phase 1 analysis, organised across the key TPACK-XD knowledge domains and the collaborative process dimension that underpin the IDT pedagogical framework.

Knowledge domain-related	Principle
Technological	• Use IDTs purposefully • Ensure interoperability and stability • Enable remote and distributed access • Support data collected from feedback
Learner	• Differentiate by level & background • Enable self-paced exploration • Support collaboration & peer-learning • Provide scaffolding & guidance
Context	• Account for budget & scalability • Ensure accessibility & inclusion • Adapt to institutional constraints • Plan infrastructure & support
Design	• Align objectives-methods-assessment • Co-design with engineers and educators • Iterative prototyping (design thinking) • Ensure usability and reliability
Content	• Strong, up-to-date domain expertise

Process	• Link theory with simulation tasks • Use authentic industrial scenarios • Embed safety & ethics
	• Foster communication across actors • Manage risks (technical, financial, etc.) • Encourage co-creation & feedback • Iterate through evidence (design thinking)

Table 2. Design principles (Source: own elaboration)

Pedagogical theories and approaches best suited for IDT-based learning environments are, according to the literature, those that emphasise active engagement, contextualised learning, and interaction with complex systems. In particular, constructivism and experiential learning provide strong theoretical foundations for IDT-based learning activities. They position learners as active participants who construct knowledge through experience, reflection, and interaction (Kolb, 2015). These approaches are especially relevant in simulation-rich and immersive contexts, where learners can explore, manipulate, and test systems in ways that mirror real-world practice. Additionally, situated learning (Lave & Wenger, 1991) supports the use of authentic, context-based scenarios, while problem-based and inquiry-based learning further enhance learners' ability to develop higher-order thinking and decision-making skills. Together, these approaches align closely with the affordances of IDTs, enabling meaningful, practice-oriented, and learner-centred educational experiences.

Core pedagogical foundation	Pedagogical modalities	Pedagogical strategies
Constructivism Experiential learning	Immersive modality Hybrid modality Differentiation	Active learning Collaborative learning Project-based learning Game-based learning Feedback and assessment

Table 3. Pedagogical approaches organisation (Source: own elaboration)

7 Conclusion

The findings of this report highlight that the integration of IDT-based learning environments in higher education is not a straightforward extension of existing practices, but a complex pedagogical endeavour requiring careful orchestration of multiple elements. The complexity of these environments demands the thoughtful selection of pedagogical approaches based on interacting factors, and the simultaneous integration of several knowledge domains (technological, learner, content, context, and design knowledge) alongside a solid understanding of pedagogical modalities and strategies. As a result, the design and implementation of IDT-based learning scenarios cannot be carried out by a single individual; rather, it is inherently a collaborative process in which co-creation, effective communication, and risk management are essential competencies.

Findings from the literature review and DBR Phase 1 interviews further show that IDT-based learning environments operate through a multi-layered pedagogical taxonomy that integrates different elements. The general pedagogical knowledge in this context is not based on adherence to a single theory, but on a dynamic configuration of learning affordances. At its core lie constructivist and experiential learning approaches, which are operationalised through pedagogical modalities defining where and when learning takes place (e.g., simulation-based or IDT environments, levels of immersion, delivery formats, and temporal structures). Learning is enabled by multiple pedagogical strategies like scaffolding, active exploration, feedback, etc. This entire configuration is shaped by the interaction of multiple knowledge domains (technological, learner, content, design, and context) and embedded within a collaborative design process involving co-creation, communication, and risk management.

The proposed framework provides a structured way for teachers to understand and operationalise this complexity through the three interconnected layers: the why (foundational pedagogical principles), the where and when (pedagogical modalities), and the how (pedagogical strategies). Together, these layers are informed by the broader ecosystem of knowledge domains and embedded within a collaborative design process. This perspective shifts the focus from selecting isolated tools or methods to designing coherent learning experiences that align environment, strategy, and objectives.

From a practical perspective, successful implementation requires attention to scenario design, modality selection, and facilitation techniques, including briefing, guided interaction, and debriefing. The possible integration of structured, modular, and open-ended scenarios across different institutional contexts (e.g., ENSAM, WUT, POLIMI) demonstrates the

Co-funded by the European Union

adaptability of IDTs to diverse disciplinary needs, while reinforcing the importance of aligning pedagogical decisions with local contexts and learner profiles. These practical aspects will be further developed throughout Phase 2 and 3 of the DBR.

In fact, IDT-based learning environments open new possibilities for assessment through the automatic capture of learner interactions, enabling more process-oriented, data-driven, and authentic evaluation practices. This allows educators to better understand not only what learners achieve, but how they learn within complex systems.

Overall, this report positions IDT-based learning environments as powerful but demanding pedagogical ecosystems. Their effective use depends not on technology alone, but on the ability of educators and institutions to integrate pedagogical, technological, and organisational dimensions into a coherent and collaborative approach to teaching and learning.

8 Limitations and Future Research

This report presents the findings from the initial phase of the DBR process undertaken within the IDT4EU project. As with any qualitative and iterative research, several limitations should be acknowledged.

First, the findings are based on a relatively small qualitative sample comprising 20 participants (11 teachers and 9 students) from three higher education institutions participating in the IDT4EU consortium. Although the sample was purposefully selected to capture diverse perspectives from different institutional contexts and thematic saturation was achieved for the objectives of this phase, the findings are not intended to be statistically generalisable. Instead, they provide rich contextual insights to inform the iterative development of the pedagogical framework in DBR phases 2 and 3.

Second, the study was conducted within only three European partner institutions representing specific disciplinary and organisational contexts. Consequently, the pedagogical principles identified may not fully capture the diversity of institutional cultures, educational systems, technological infrastructures, or disciplinary practices found across other higher education and vocational education settings.

Third, this report reflects an early stage of the DBR process. While the proposed pedagogical framework has been informed by empirical evidence and expert interpretation, its effectiveness has not yet been fully validated through large-scale implementation. Subsequent DBR cycles will involve pilot implementations, iterative refinement, and systematic evaluation to examine the framework's practicality, usability, and impact on teaching and learning across multiple educational contexts.

Finally, as with all qualitative thematic analyses, the interpretation of interview data involves researcher judgement. Although the coding process followed established qualitative analysis procedures, was conducted collaboratively by members of the research team, and findings were discussed throughout the analysis process to enhance credibility, it is acknowledged that alternative interpretations of the data may also be possible.

Future research will focus on implementing and evaluating the IDT4EU pedagogical framework through successive DBR iterations across diverse HEI and VET contexts. These studies will examine the framework's usability, relevance, and practicality, as well as its effectiveness in supporting the design of high-quality IDT-based learning environments. Testing the framework across a wider range of disciplines, institutions, countries, and learner populations will further strengthen its transferability and contribute to the development of evidence-informed design principles for the pedagogical integration of Immersive Digital Twins.

References

Biggs, J., & Tang, C. (2011). *Teaching for quality learning at university* (4th ed.). Open University Press.

Bransford, J. D., Brown, A. L., & Cocking, R. R. (Eds.). (2000). *How people learn: Brain, mind, experience, and school*. National Academy Press.

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. Qualitative research in psychology, 3(2), 77-101.

Bruner, J. S. (2009). The Process of Education. Harvard University Press.

Ciriza-Mendívil, C. D., et al. (2022). Technological pedagogical content knowledge: A framework for teacher knowledge. *Frontiers in Education, 7*, Article 868314.

Cuvelier, L., Dangouloff, N., Fernagu, S., & Paggetti, M. (2025). Vademecum JENII. https://doi.org/10.5281/ZENODO.17752475

Daineko, Y. (2025). *Immersive technologies and digital twins in education* [Paper-presentation]. CEUR-WS, Vol. 4014.

Dickerson, C. (2022). Using a teacher knowledge framework to connect teaching, learning and professional development. *Frontiers in Education, 7*, Article 856153.

Grigaliūnienė, M., et al. (2024). Pedagogical content knowledge (PCK) in higher education: A systematic scoping review. *Education Sciences, 14*(4), Article 217.

Country Comparison Bar Charts. (n.d.). Geert Hofstede. Retrieved 25 March 2026, from https://geerthofstede.com/country-comparison-bar-charts/

Hofstede, G. (2013). Culture's consequences: Comparing values, behaviors, institutions, and organizations across nations (2. ed. [Nachdr.]). Sage.

Hofstede, G. H., Hofstede, G. J., & Minkov, M. (2010). Cultures and organizations: Software of the mind: intercultural cooperation and its importance for survival (3rd ed). McGraw-Hill.

Ifenthaler, D., & Yau, J. Y.-K. (2020). Utilising learning analytics to support study success in higher education: A systematic review. Educational Technology Research and Development, 68(4), 1961–1990. https://doi.org/10.1007/s11423-020-09788-z

Jarni, N. (2024). A futures perspective on learning and teaching in higher education. *Future Education and Research in Higher Education, 1*(1), 1–15.

Koehler, M. J., Mishra, P., Kereluik, K., Shin, T. S., & Graham, C. R. (2014). The Technological Pedagogical Content Knowledge Framework. In J. M. Spector, M. D. Merrill, J. Elen, & M. J. Bishop (Eds), Handbook of Research on Educational Communications and Technology (pp. 101–111). Springer New York. https://doi.org/10.1007/978-1-4614-3185-5_9

Kolb, D. A. (2015). Experiential learning: Experience as the source of learning and development (2nd ed.). Pearson Education.

Laurillard, D. (2012). *Teaching as a design science: Building pedagogical patterns for learning and technology*. Routledge.

Lave, J. (with Internet Archive). (1991). Situated learning: Legitimate peripheral participation. Cambridge [England] ; New York : Cambridge University Press. http://archive.org/details/situatedlearning0000lave

Lu, Y. (2024). Teachers' pedagogical content knowledge in English language teaching in higher education. *Asian Journal of University Education, 20*(1), 201–215.

Meij, E. (2025). Which principles of learning do teachers and teacher educators deem important? *Teaching and Teacher Education, 133*, Article 104488.

Mishra, P., & Koehler, M. J. (2006). Technological Pedagogical Content Knowledge: A Framework for Teacher Knowledge. Eachers College Record, 108(6), 1017–1054.

Mishra, P. (2019). Considering Contextual Knowledge: The TPACK Diagram Gets an Upgrade. Journal of Digital Learning in Teacher Education, 35(2), 76–78. https://doi.org/10.1080/21532974.2019.1588611

Ning, G., et al. (2024). Exploration of the application and practice of digital twin in engineering education. *Sustainability, 16*(23), 10312. https://doi.org/10.3390/su162310312

Obae, C. (2026). TPACK-XD: Elements to Consider When Creating Curriculum in a Metaverse-based Higher Education Learning Environment. Seminar.Net, https://doi.org/10.7577/seminar.6205

Obae, C., Dai, C.-P., & Leong, P. (2025). Bridging the divide: Immersive virtual spaces for hybrid learning in remote teacher education. Education in the North, Arctic Futures: innovations in education for social justice and sustainability(Volume 32(3)). https://doi.org/10.26203/4CZ2-HZ16

Obae, C., Fleury, S., Bondesan, P., Auchet, A., & Rey, N. (in press). Contextual Knowledge. The gap between academic research and practical issues. Learning, Media and Technology.

OECD. (2021). *Teaching as a knowledge profession: Studying pedagogical knowledge across education systems.* OECD Publishing.

Pathak, R. K., & Upadhyay, P. (2024). Integration of digital twin technologies in education for experiential learning: Benefits and challenges. *International Research Journal on Advanced Engineering Hub, 2*(3), 442-449. https://doi.org/10.47392/IRJAEH.2024.0064

Piaget, J. (1970). Science of education and the psychology of the child. Orion Press.

Prosser, M., & Trigwell, K. (1999). *Understanding learning and teaching: The experience of higher education*. Open University Press.

Ramsden, P. (2003). *Learning to teach in higher education* (2nd ed.). Routledge.

Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. *Educational Researcher, 15*(2), 4–14.

Shulman, L. S. (1987). Knowledge and teaching: Foundations of the new reform. *Harvard Educational Review, 57*(1), 1–22.

Siemens, G., & Baker, R. S. J. d. (2012). Learning analytics and educational data mining: Towards communication and collaboration. Proceedings of the 2nd International Conference on Learning Analytics and Knowledge, LAK '12, 252–254. https://doi.org/10.1145/2330601.2330661

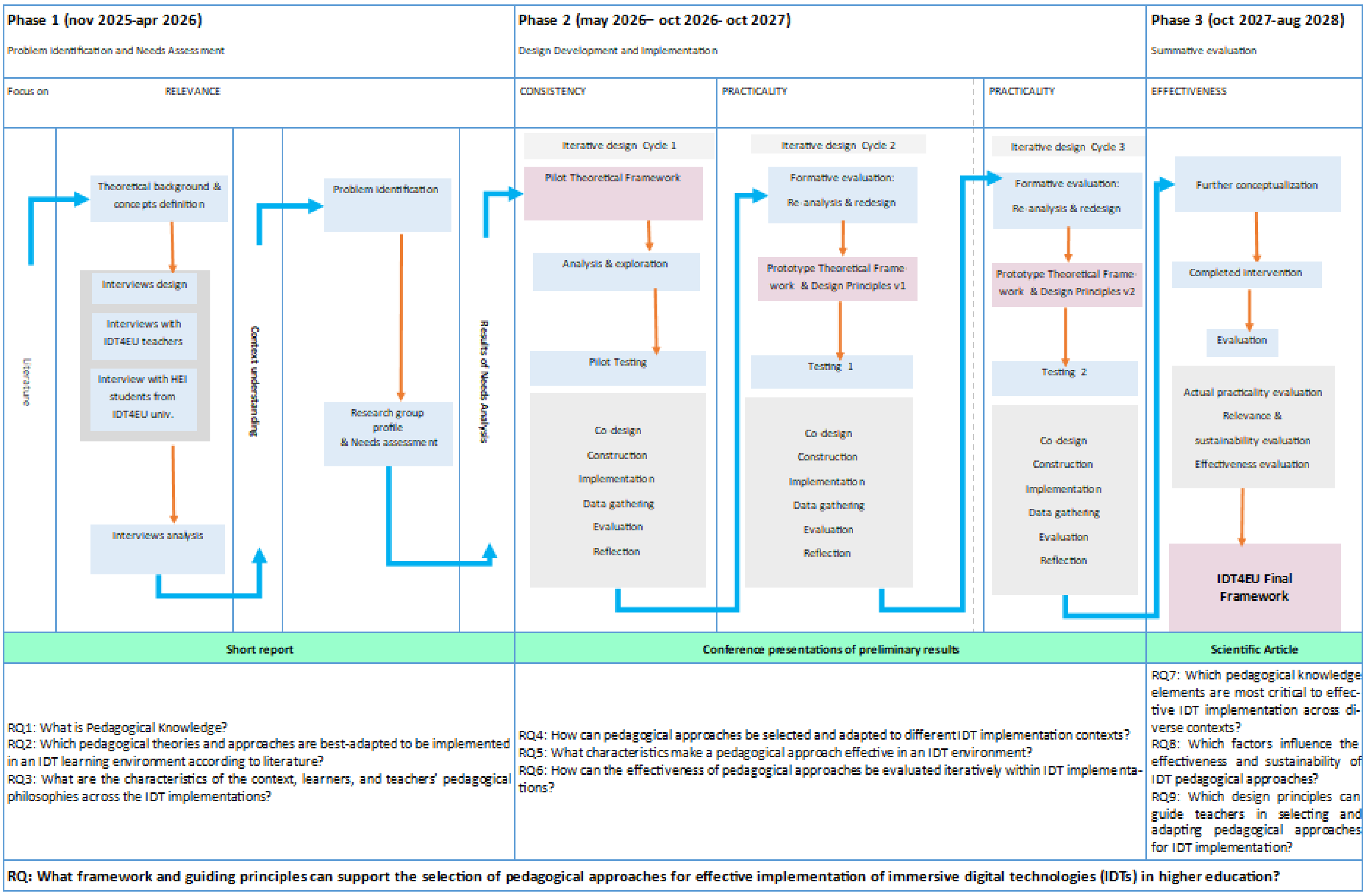
Vygotsky, L. S., & Cole, M. (1978). Mind in society: Development of higher psychological processes. Harvard university press.

Wiggins, G. (1998). Educative Assessment. Designing Assessments To Inform and Improve Student Performance. Jossey-Bass Publishers, 350 Sansome Street, San Francisco, CA 94104 ($32.95); fax: 800-605-2665; Internet: http://www.josseybass.com. https://eric.ed.gov/?id=ed418997

Co-funded by
the European Union

Annexes

Annex 1 – DBR process



Co-funded by the European Union

Annex 2 – themes, categories and codes selection

Themes	Categories	Codes selection
Core pedagogical foundation	Differentiation strategies; Engagement; Supports for students	Different strategies for different types of learners; Going step by step to support all types of learners; having breaks is essential; Heterogeneous groups to address learners differences; not specific plan to support different types of learners; Same strategy for all the learners; special arrangements for colour blind students; students attributes' impacts the course designing; o active participation increases engagement; competitions increase engagement; Flipped classrooms increase engagement; organise competitions to increase engagement; Simulation increases engagement to learning; Teacher's better voice engages more; Thinking about final results increases engagement; uses different methods to increase engagement; VR can increase engagement; adjustment of lesson planning based on learner attributes; adjustment of pace for learners; administrative procedures need to be followed; Asking questions to learn about students' prior knowledge; availability for questioning in needed; Basic technical support from the institution; different support based on learning outcomes and class type; Examples help learning; getting students' feedbacks to enhance the lesson planning; Identification of learner attributes; Live transcription helps in online classes; need to be graded frequently; problem solving consultation to support students; sharing materials to support students; support students with in-class discussion; supporting students beyond class hours; supports for advanced learners; tutorial sessions to support students, visualisation helps learning
Pedagogical modalities	Use of simulation and immersive technologies; Educational technologies	Active participation increases engagement; competitions increase engagement; Flipped classrooms increase engagement; organise competitions to increase engagement; Simulation increases engagement to learning; teacher's better voice engages more; Thinking about final results increases engagement; uses different methods to increase engagement; VR can increase engagement; integrating digital tools for learning; technologies in use
Pedagogical strategies	Current teaching methods; current status of active learning; Preferable teaching-learning method	Assessment procedure is very important; choosing teaching strategy; classes ends with small assessments; collaboration helps learning the most; combination of content and technological knowledge; course design process; currently does group works; currently using active learning; currently using collaborative learning; currently using gamification; currently using immersive technologies; currently using interactive learning through discussion; Currently using lab-based classes; currently using learning by doing; Currently using lecture method; currently using project-based learning; currently using simulation modelling; currently using simulation tools related to manufacturing process; currently using virtual reality headset; currently using VR

Co-funded by the European Union

		environment to teach; feedback is essential; Identifies takeaways at the end of class; incorporating engagement and interactivity; learning by doing for engaging the learners; Lecture followed by practice was most successful class; lesson design process; Mixes different methods in class; Role playing as active learning; students' presentation/project at the last part of the class; teaching strategies depend on learning goals; tries to uphold student's social skill; active learning is the main point; prefers active participation; prefers game-based method; prefers learning by doing; prefers lectures followed by exercises; prefers physical presence over online class; prefers practical projects; prefers project-based learning; prefers simulation-based learning; prefers small practice sessions after lecture
TPACK-XD domains	Pedagogical challenges; impacts of teaching context; benefits of IDTs; Definition of pedagogical knowledge; Support for teachers; content knowledge; flow of the lesson; lesson design process; health issues related to ITD use; suggestions for IDT implementation; Teaching competencies; Teachers' technical Knowledge; Experience with IDTs; Important skills for teachers	Challenges to meet pedagogical expectation; authority's permission is essential for doing something innovative; impacts of institutional policies; impacts of society and environment; independent of disciplinary standards or educational policies; independent of institutional policies, resources or culture; Insufficient infra-structural facilities; National accreditation board has huge impact or teaching-learning; rigid rules of the institute; teaching environment impacts on the speed of teaching; teaching method depends on university rules; efficient in numeric calculation; experiences VR as a part of a research project; experiential learning through IDTs will help; IDTs allows errors by learners; IDTs are good for labs and tutorials; IDTs are helpful for learning; IDTs can blur the geographical differences in learning; IDTs enable experiential learning; IDTs help in-depth learning; IDTs helps memorising; IDTs increase engagement; immersion was effective for learning; immersive environments to ensure safe operations of machines; multidimensional usages of IDTs; simulations make learning easier; Trying to make students aware about dangers with IDTs; use of IDTs is cost effective; VR technology enables remote learning; Definition of Pedagogical Knowledge; necessary supports for teachers; teacher training is essential; content knowledge is very important; updates content knowledge regularly; brief concept with explanation of application; connecting different topics; from the basic to the advanced; lesson design process; dizziness; eye problem; headache; nausea; people with motion sickness may have difficulty; some can feel sick; AI power needs to incorporate; collaboration among colleague; collaboration among colleagues is important; contextualization; introducing a concept with IDTs; it is the best to combine VR with reality; list of instruction is helpful; more free time to explore; needed to realize the purpose; PBL through IDTs; possible effective teaching methods with IDTs; teaching methods in IDTs are similar to in-person teaching; lesson design process; comfortable user of technology; confident user of IDTs; not very comfortable with technologies; technical support needed; University level collaboration is suggested; want to expand experience with IDTs; wants to work virtually; o Discovering the environment with IDTs worked well; enjoyed the immersive presentation; experienced IDTs for once; experienced IDTs in study visits; experienced

		simulation is industrial context; experienced VR applications in other schools; experiences VR as a part of a research project; experiment went better with high school students; generation phenomenon; group work was successful in IDT environment; IDTs used for small scale sessions; limited experimental use of Digital Twins; little use of AI; more supportive to the secondary level students; optimistic about IDTs; positive feedback from secondary school students; practiced ITDs in lab not used in classroom; project-based IDT initiative; secondary level students adapted quickly; tested with different levels of students; used immersive technology for university education; using IDTs for training purposes; worked well during partial use; young people with mild autism was comfortable in IDT environment; adaptation skill is essential for teachers; communication skill is important for teachers; having motivation is important for the teachers; it's important to learn to use the technology properly; knowing the technology is important skill for teachers; resilience with proper; organization skill is important for teachers; social skill is important for teachers; teacher should be open-minded
Cross-cutting competencies	Teachers' challenges; challenges of IDT implementation; technical challenges of IDTs; Learners' challenges	Difficult to teach complex topics if there is nothing to show; lack of skill; large classes for master degree; mental overload is a problem for teachers in Poland; teaching difficult topics; accessibility issue; easy to used but not to learn/teach; efficiency of VR is essential; efficient in numeric calculation; extremely time consuming; financial constraint; financial limitation of the institution; immersive model must be well framed; limited opportunities for real-time simulations; reliability issue; risk due to lack of financial support; speed may be a problem; technical complexity; technical uncertainty; understanding commands was challenging initially; change of parameters can affect the results; difficult to understand at the beginning, little bugs; technical complexity; difficult to concentrate on lecture, sometimes students lack motivation