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The *Art Nouveau Path*: Promoting Sustainability Competences Through a Mobile Augmented Reality Game

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Abstract

This paper presents a qualitative case study on the design, implementation, and validation of the *Art Nouveau Path*, a mobile augmented reality game developed to foster sustainability competences through engagement with Aveiro's Art Nouveau built heritage. Grounded in the GreenComp framework and developed through a Design-Based Research approach, the game integrates location-based interaction, narrative storytelling, and multimodal augmented reality and multimedia content to activate key competences such as systems thinking, futures literacy, and sustainability-oriented action. The game was validated with 33 in-service schoolteachers, both through a simulation-based training workshop and a curricular review of the game. A mixed-methods strategy was used, combining structured questionnaires, open-ended reflections, and curricular review. The findings revealed strong emotional and motivational engagement, interdisciplinary relevance, and alignment with formal education goals. Teachers emphasized the game's capacity to connect local identity with global sustainability challenges through immersive and reflective experiences. Limitations pointed to the need for enhanced pedagogical scaffolding, clearer integration into STEAM subjects, and broader accessibility across technological contexts. This study demonstrates that these games, when grounded in competence-based frameworks and inclusive design, can meaningfully support multimodal, situated learning for sustainability and offer valuable contributions to pedagogical innovation in Education for Sustainable Development.

Keywords: Art Nouveau Path; Augmented Reality (AR); Mobile Augmented Reality Game (MARG); multimodal learning; cultural heritage education; case study; Design-Based Research (DBR); Greencomp; sustainability competences; Education for Sustainable Development (ESD)

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1. Introduction

Educational systems worldwide are increasingly being prompted to navigate the intricate issues concerning Education for Sustainable Development (ESD). These challenges, ranging from environmental degradation and resource depletion to deepening social inequalities, require educational responses that go beyond cognitive understanding. In this scenario, ESD has gained momentum as a revolutionary method that surpasses cognitive comprehension alone to include the competences, like the Knowledge, Skills, and Attitudes (KSA), necessary for critical engagement with sustainability concerns [1]. Global initiatives for worldwide policy, notably as the United Nations' Sustainable Development Goals [2] and the European Green Deal [3], reinforce the essentiality of giving citizens access to the

instruments required to spark change in their own communities. It is imperative that these endeavors are initiated during early childhood, within educational institutions, and are pursued in a manner that encompasses a lifelong learning approach within professional contexts [4].

In parallel, the rapid evolution of digital technologies is reshaping educational strategies, creating novel paths to connect structured curricula with real-world activities. Within this context, augmented reality (AR) has surfaced as a valuable instrument for enhancing place-based education by overlaying virtual data onto tangible environments. AR facilitates situated, multimodal, and interactive learning experiences that blend cognitive engagement with emotional resonance [5–7]. When used in game-based learning activities, AR can enhance learner motivation, promote interdisciplinary inquiry, and transform urban spaces into dynamic pedagogical environments [8–10].

One area where this potential is particularly significant is heritage education. Built cultural heritage offers a meaningful context for engaging with questions of identity, memory, continuity, and transformation [11–14]. Furthermore, it provides a substantial context for the exploration of sustainability-related themes, including environmental stewardship, adaptive reuse, and community resilience [15,16]. When enhanced with AR, heritage education has the potential to evolve into an emotionally resonant and cognitively meaningful experience that stimulates critical reflection on the interplay between the past, present, and future [17–19]

In this context, the *Art Nouveau Path* was developed as a mobile augmented reality game (MARG) designed to foster competences for sustainability through the valuing of Aveiro's Art Nouveau heritage. The MARG was developed within the EduCITY project https://educity.web.ua.pt/) at the University of Aveiro, Portugal. The main goal of this MARG is to guide players, primarily students, through a walking path across eight Art Nouveau landmarks (points of interest) in the city of Aveiro, Portugal, as presented in Figure 1.

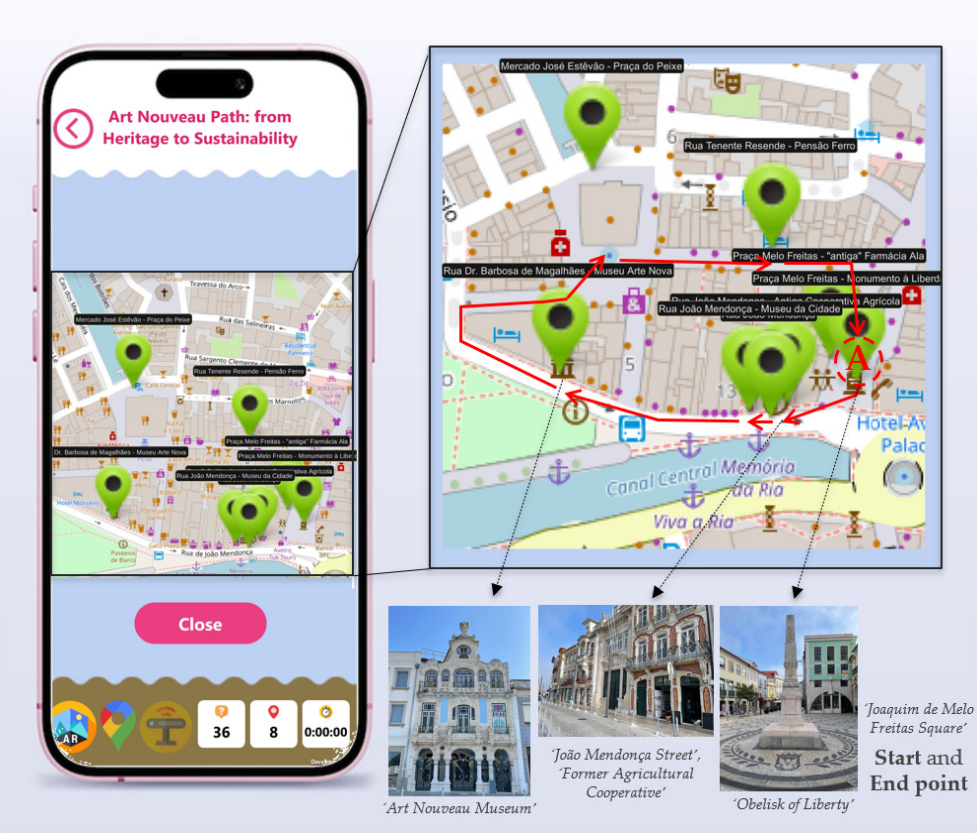

Figure 1. *Art Nouveau Path* map in EduCITY app (in-game screenshot, path, and three monuments).

At each point of interest, players engage with location-based content, including historical overlays, AR and multimedia content, narrative prompts, and reflective quizzes designed to link architectural details with ecological and civic themes, as well as interdisciplinary Portuguese curriculum content.

A conceptual and distinctive feature of this MARG is its strategic alignment with GreenComp, the European Sustainability Competence Framework [20]. This framework outlines twelve competences, which are grouped into four broader dimensions: (a) '*Embodying Sustainability Values*', focused on personal values, attitudes, and motivation to act; (b) '*Embracing Complexity in Sustainability*', encouraging systems thinking and critical and complexity analysis; (c) '*Envisioning Sustainable Futures*', which involves imagining, creating, and planning for sustainable alternatives; and (d) '*Acting for Sustainability*', focused on individual and collective transformation. Each interaction in the *Art Nouveau Path* was designed to reflect these dimensions, thereby enabling learners to connect esthetic appreciation, local-based history, and cultural memory with systems-thinking, future-oriented action, and to reflect on local and global sustainability concerns [20–23].

Although the target audience of this MARG consists of students (eighth grade and above), the present study focuses on its development and validation phase conducted with teachers (T1-VAL and T1-R) as part of the pre-implementation stages.

This paper presents a qualitative case study, guided by the principles of Design-Based Research (DBR), exploring how this MARG can support the activation of competences within the broader context of ESD. While the DBR approach was used to guide its iterative design and validation, this study focused on the empirical validation of the *Art Nouveau Path* by a group of 30 in-service teachers from diverse disciplinary backgrounds (T1-VAL). This validation was part of a teachers' training course regarding sustainability education based on heritage, which included engagement with the game features in a simulated environment. Also, a curricular review was undertaken by another three teachers (T1-R).

The aim of this study is to investigate the potential of the *Art Nouveau Path* MARG to activate sustainability competences through immersive and multimodal learning experiences. Developed as a context-aware educational tool, this MARG integrates location-based interaction and rich media content to engage learners with cultural heritage sites in the urban landscape.

Originally designed for educational purposes, the game explores the pedagogical value of multimodal interaction by combining spatial, visual, auditory, and narrative elements. These dimensions are intended to enhance player engagement, foster interdisciplinary learning, and promote critical reflection on civic responsibility and environmental sustainability.

The study is grounded in the principles of human–computer interaction and competence-based education, contributing to the growing body of research on how interactive technologies can transform educational practices within culturally situated and sustainability-oriented contexts.

This study is guided by two interconnected research questions:

1. How do multimodal and location-based interactions within the *Art Nouveau Path* MARG influence learner engagement and the player experience?
2. How can the MARG support the development of sustainability competences through context-aware educational interactions?

The paper is structured into six sections, each aiming to address the research questions through a theoretically grounded and methodologically rigorous lens. The second section presents the theoretical framework from four interconnected domains: AR in education, multimodal interaction, sustainability competences, and heritage-based learning through serious games. These areas constitute the conceptual foundations upon which the design and teachers' validation (both TI-VAL and T1-R) of the *Art Nouveau Path* are based. The

third section outlines the research design, with a particular focus on DBR methodology, and the activities conducted during the validation phase. The fourth section provides the empirical findings gathered from both the training session with in-service teachers (T1-VAL) and by the teachers' curricular review (T1-R). In the fifth section, the study's results are critically synthesized to evaluate the pedagogical effectiveness of the game in supporting the activation of sustainability competences. Finally, the sixth section discusses the study's contributions, acknowledging methodological limitations and proposing directions for future research and pedagogical innovation.

To rigorously address the research questions, it is essential to establish a coherent theoretical foundation. The educational potential of AR-mediated, multimodal learning, particularly in fostering sustainability-related competences, must be examined through relevant conceptual models and empirically validated frameworks. Accordingly, the following section provides a cross-disciplinary synthesis of this study's conceptual and methodological approach.

2. Theoretical Framework and Related Work

This section and its subsections establish the conceptual and empirical grounds guiding the design and validation of the *Art Nouveau Path* MARG.

Its pedagogical development draws upon four interrelated domains: (1) multimodal and context-based learning enabled by AR technologies; (2) the GreenComp framework as a foundation for competence-based sustainability education; (3) the pedagogical potential of heritage and place-based learning; and (4) the design and validation of serious games.

These domains are connected by a shared commitment to transformative learning [20,24,25], in which Knowledge, Skills, and Attitudes (the three GreenComp dimensions of competences) [20] are co-constructed through critical reflection within authentic, context-rich environments.

2.1. Multimodal and Context-Based Learning Through Mobile Augmented Reality

Mobile AR facilitates the overlay of digital media, like visuals, text, audio, and animations, onto physical environments, thus supporting deeply contextualized and multimodal learning experiences [5]. Grounded in constructivist and situated learning theories [26,27], this approach positions learners as active participants in meaning-making, with knowledge acquisition enhanced when embedded in real-world contexts.

Recent empirical studies sustain the potential of AR to foster learner engagement, spatial reasoning, and conceptual understanding, particularly in outdoor and place-based educational settings [7,18,19]. In cultural heritage contexts, AR also supports affective and cognitive engagement by allowing learners to interact in situ with historical narratives, material culture, and built environments [18,19].

The Art Nouveau Path uses context to anchor interactive, multimodal content at specific urban locations (points of interest). This spatial anchoring reinforces the interdependences between Place, History, and Knowledge. The MARG encourages interdisciplinary exploration, prompting learners to explore Architecture through the lenses of Art, Ecology, History, Mathematics, Natural Sciences, and Civic Education. In the present study, these learning affordances were experienced and validated by both the 30 in-service teachers (T1-VAL) and by the 3 teachers that performed the curricular review of the MARG (T1-R). The teachers' feedback contributed to the ongoing refinement of the MARG regarding educational purposes.

2.2. Operationalizing GreenComp in Context-Aware Heritage Education

The GreenComp framework [20] provides a coherent, flexible model for structuring sustainability learning across formal and informal education. It defines twelve interrelated

competences clustered into four dimensions: '*Embodying Sustainability Values*', '*Embracing complexity in Sustainability*', '*Envisioning Sustainable Futures*', and '*Acting for Sustainability*'. Designed to be adaptable, GreenComp encourages diverse pedagogical approaches and local curricular implementation [20].

The design of the *Art Nouveau Path* and the evaluation of its pedagogical relevance were both informed by the GreenComp framework. A dedicated instrument, the *Art Nouveau Path GreenComp-based Questionnaire (GCQuest)*, was developed for this purpose (available at: https://doi.org/10.5281/zenodo.15919739). However, the data collected using this questionnaire are not analyzed in the present article.

While it is evident that not all the MARG elements are mapped in a one-to-one correspondence with GreenComp dimensions, it is noteworthy that a significant proportion of the 36 quiz-type questions involved in the Art Nouveau Path were conceptually aligned during the development process to reflect key sustainability competences, particularly those related to systems thinking, ethical values, and future-oriented reasoning and action. The pedagogical alignment in question aims to activate learner engagement with sustainability in contextually meaningful ways.

As an example, one question is related to Aveiro's 1938 flood. In this question, players analyze a video and AR-enhanced archival images to reflect on the causes and consequences of urban vulnerability, thereby activating systems thinking. Also, another question involves the '*Arcos Fountain*' (Figure 2), prompting reflection on historical and contemporary water use and encouraging critical thinking about equity, infrastructure, and environmental ethics. At the 'Aveiro's City Museum' (Figure 3), players are triggered to reflect on adaptive heritage reuse strategies, balancing cultural preservation and sustainable design. At the same point of interest, another scenario, namely one concerning acid rain and material degradation, aims to highlight civic responsibility and awareness of environmental and climate changes.

Figure 2. '*Arcos Fountain*' (early 20th century), in-game narrative flow.

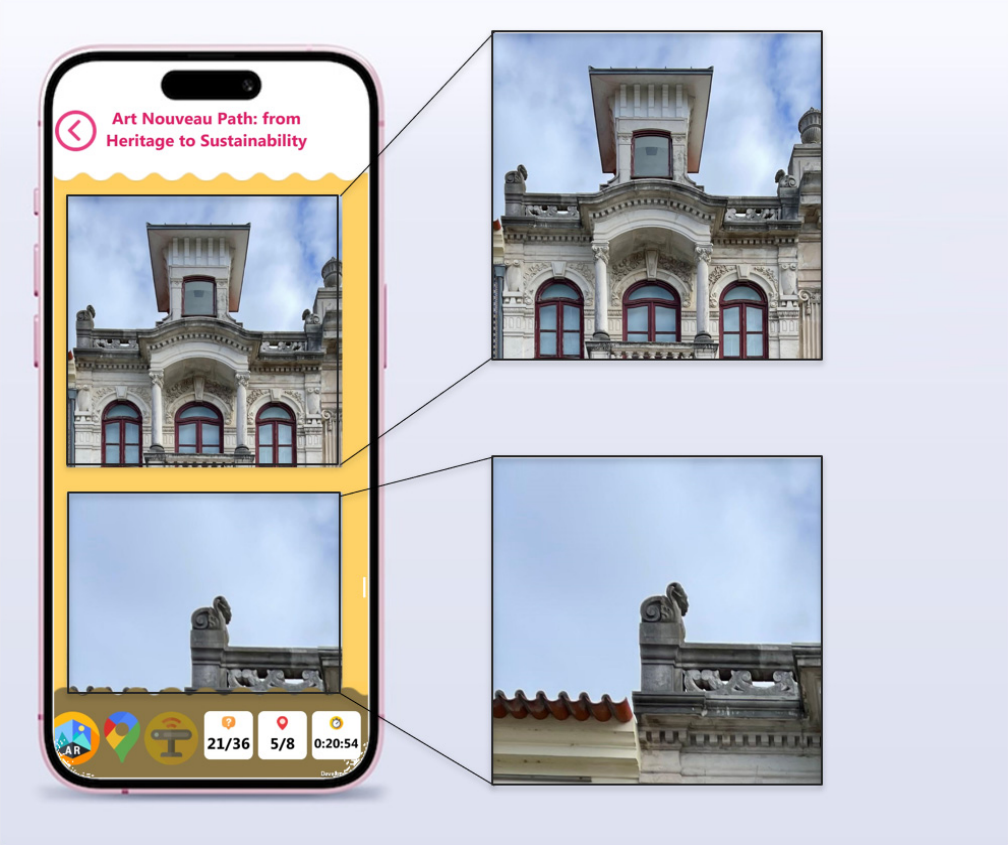

Figure 3. *'Aveiro's City Museum'* details (in-game figures).

To promote futures literacy, speculative design prompts are integrated throughout the MARG. One question invites players to imagine electric-powered *'[typical]'* boats (Figure 4), symbolizing a clean energy transition rooted in local heritage, as students can see in the real context (Figure 5). Other questions focus on envisioning sustainable urban futures and the preservation of historical districts amid climate change. Through these situated, interactive challenges, abstract sustainability competences become concrete, emotionally resonant, and actionable [20–23,28,29].

2.3. Heritage as a Living Space for Sustainability Learning

Built heritage can be a powerful medium for exploring the intersection of culture, memory, and sustainability. Architectural forms and urban spaces embody local identity, adaptation, and resilience [15,25,30]. To serve as a transformative educational space, heritage must be reinterpreted not as static legacy, but as a dynamic and living context for civic engagement and critical reflection [13,31,32].

Françoise Choay [11,12] frames heritage as a cultural construct, continuously redefined by societies' evolving relationship with their own past.

The *Art Nouveau Path*'s pedagogical approach is underpinned by the same perspective, discussing Aveiro's Art Nouveau heritage as dialogical space. Players are invited to engage with multimodal media and historical "glints of the past", illuminating forgotten or overlooked urban spaces and stories. As example, at the *'Former Agricultural Cooperative'* (Figure 6), players can, with AR content, explore the building's history, its past and present functions, and curiosities, while exploring the unique and exquisite tile façade of the *'Fonte Nova Factory'* and calculate the cymatium area.

Nearby, at the 'Aveiro's City Museum', players can explore the naturalistic stonework (this detail triggers AR content, as presented in Figure 7), and learn about material degra-

dation and restoration options, linking architectural conservation to environmental sustainability and introducing students to related professional fields.

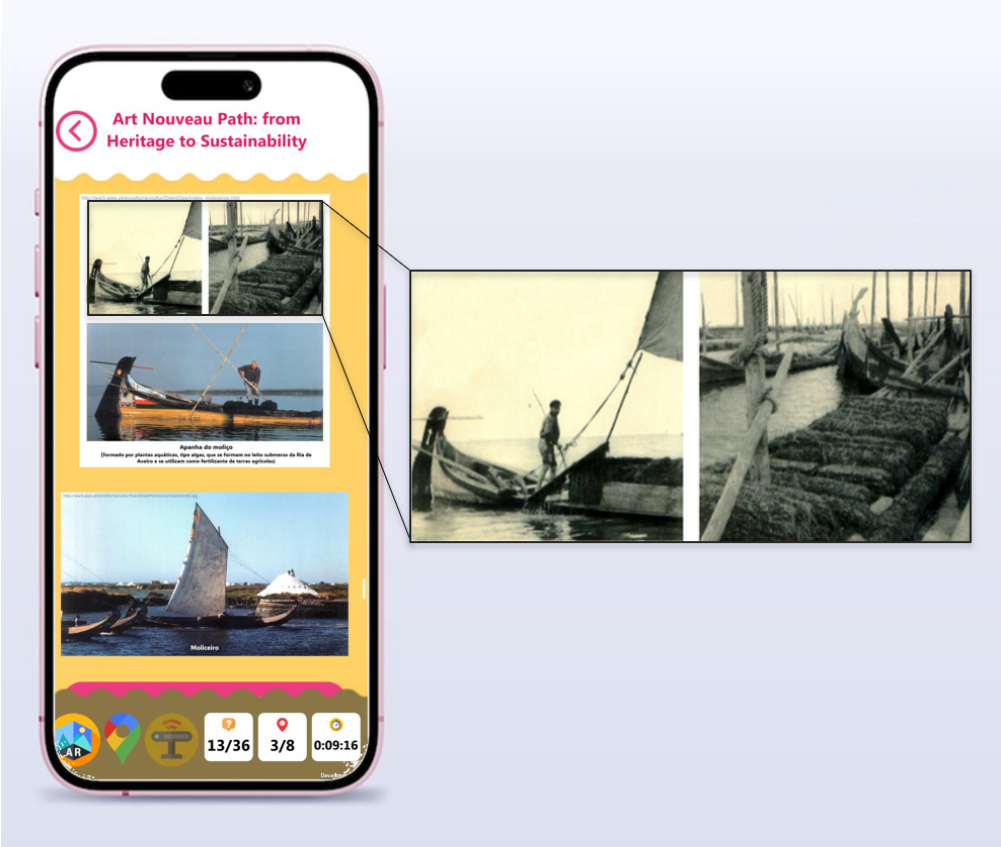

Figure 4. *'moliceiro'* boats (in-game figures).

Figure 5. In-place electric charging station for *'moliceiro'* boats (in context).

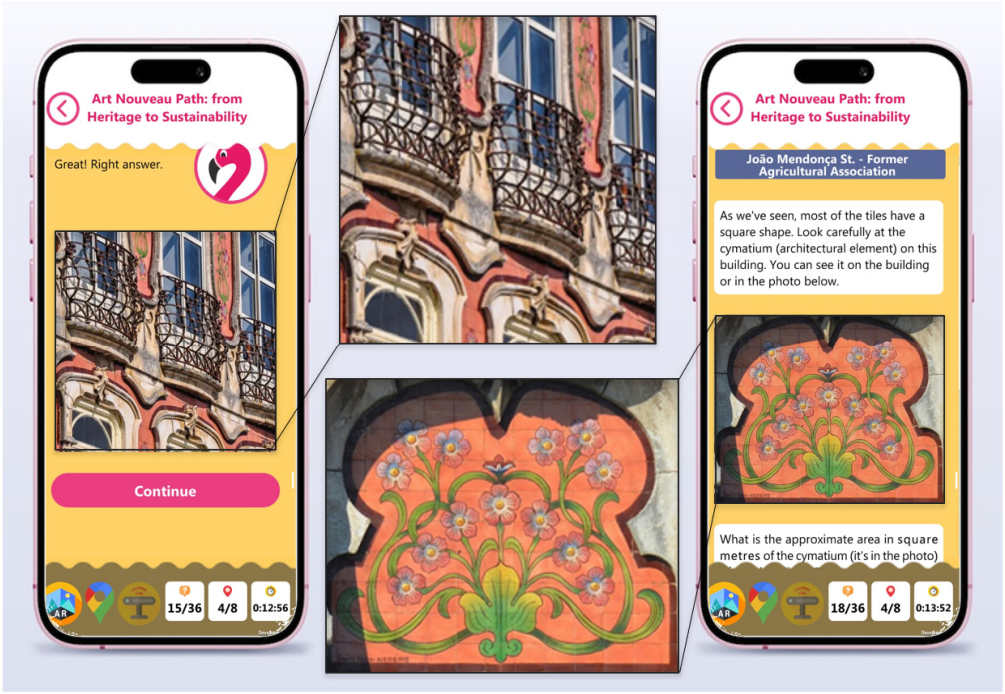

Figure 6. '*Former Agricultural Cooperative*' details (in-game figures).

Figure 7. Architecture-detail AR marker that triggers AR content about 'Aveiro's City Museum' (in-game figures).

At the old '*Fish Market*' (Figure 8), players, as well as being invited to look at the iron-building's architectural details, reflect on overfishing and the depletion of global fish stocks, and are directly presented with sustainable alternatives like aquaculture or fishing stock management [33].

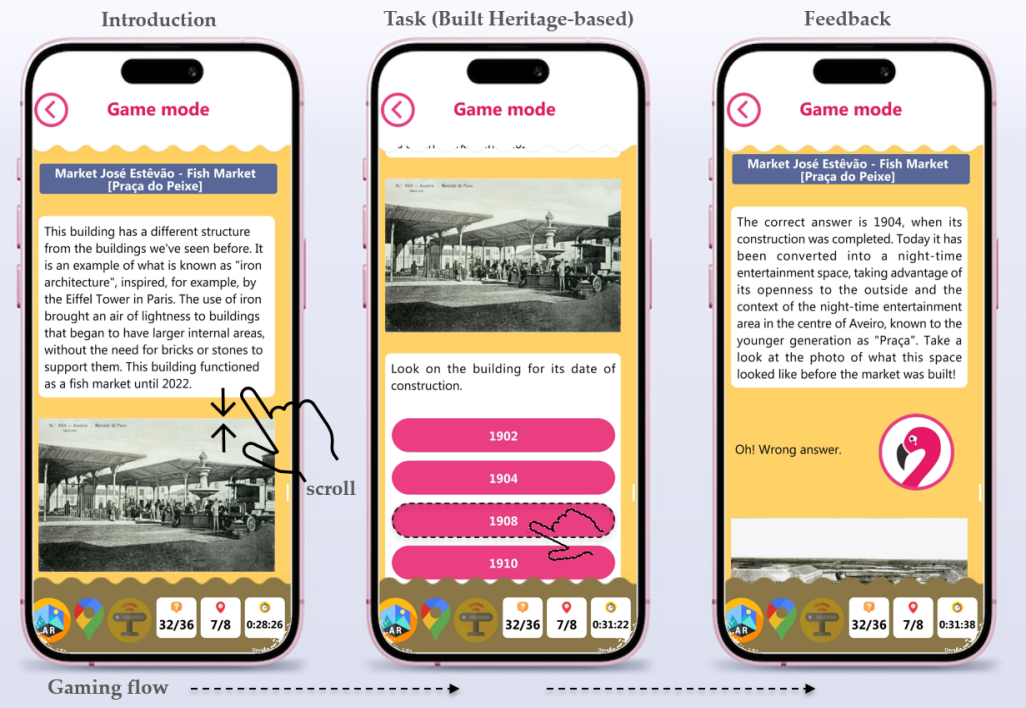

Figure 8. Game flow at the '*Fish Market*' (in-game figures).

This educational approach aligns with critical place-based education [34,35], which considers that transformative learning is most effective when situated in the everyday spaces that learners inhabit. By embedding GreenComp competences into the local cultural context, the game bridges local and global issues, rendering sustainability relevant, comprehensible, and conducive to participatory action.

2.4. Validating the Art Nouveau Path as a Sustainability-Focused Serious Game

Serious games are increasingly recognized as effective educational tools for sustainable development. They can foster systems thinking, critical reflection, and engagement through participatory and challenge-based interactions [36–38]. When combined with AR and local and cultural heritage, these games can simulate real-world complexity, offering immersive, value-rich experiences that cultivate, among other values, empathy, responsibility, and active citizenship [38].

To ensure pedagogical effectiveness, it is essential to conduct robust validation. Based on the DBR approach [39,40], the *Art Nouveau Path* underwent several iterative refinements and a final validation. Although the game is intended for students (eighth grade and above), the present study focuses on its validation with teachers. This phase involved two complementary activities: (1) a simulation-based training session with 30 in-service teachers (T1-VAL), who explored the full game and completed an evaluative questionnaire; (2) a structured curricular review carried out by three additional teachers (T1-R). These procedures aimed to assess pedagogical alignment, curricular relevance, user engagement, and interdisciplinary potential.

To facilitate this validation rationale, Table 1 presents the pedagogical structure of the Art Nouveau Path game by points of interest. It outlines the spatial elements, tasks, and media used, and their alignment with both disciplinary and transversal competences. The transversal competences were mapped based on national policy documents and international (EU, OECD, UN, UNESCO) frameworks.

Table 1. The design of the *Art Nouveau Path* MARG by area/point of interest: Built Heritage, Narrative, Curriculum, In-Game Activities, GreenComp Alignment, and Transversal Competences.

Area/Point of Interest	Built Heritage (Art Nouveau)	Narrative/Multimodal Content	Task Typology/ Curriculum Area	Illustrative In-Game Activities	GreenComp Competences	Transversal Competences
Joaquim de Melo Freitas Square (Start)	'*Obelisk of Liberty*'; '*Arcos Fountain*'; '*Former Ala Pharmacy*'	Urban Memory and Identity; Art Nouveau style; esthetics and nature; AR and videos	Identity recall; temporal analysis; water reflection	Interpreting flood photos; comparing past/present water systems; identifying motifs and materials in façade; decoding stone and tile works	Systems thinking; critical thinking; valuing sustainability; exploring complexity	Historical reasoning; emotional engagement; visual literacy; critical observation
João Mendonça Street/City's Lagoon Central Canal	'*Former Agricultural Cooperative*'; '*[City]'s City Museum*'	Salt commerce; 'typical' boats; historic street; Urban Memory and Identity; Sustainability and Action	Historic measurement unit conversion; naming; place reading; material classification; applied geometry; heritage use identification; restoration roles; Natural Sciences; History	Façade analysis; geometry; construction materials; adaptive reuse of historical building; classifying limestone types; discussing sustainable building materials; comparing past/present building uses; identifying restoration techniques	Systems thinking; strategic problem-solving; responsible consumption; adaptability; strategic thinking	Contextual numeracy; place-based awareness; design thinking; resource awareness; strategic interpretation; heritage literacy
Barbosa Magalhães Street	'*Art Nouveau Museum*'	Ricochet line; vertical stone-garden; decoration styles; Cultural Esthetics and Nature	Art Nouveau style analysis; nature–art synthesis; Natural Sciences; History	Exploring façade botanical elements and ricochet line symbolism	Valuing sustainability; promoting nature	Creativity; visual interpretation
Old 'Fish Market'	'*Fish Market*'	Architectural elements; Sustainability and Action	Architectural quiz; consumption reflection	Fish resource depletion and solutions	Responsible consumption; critical thinking	Data interpretation; responsible reflection
'Pensão Ferro' (old guesthouse)	'*Pensão Ferro' (old guesthouse)*	Decorative Art Nouveau façade; Cultural Esthetics and Nature	Visual analysis; stylistic interpretation	Observing Art Nouveau façade; discussing stylistic patterns	Critical thinking; exploring complexity	Pattern recognition; esthetic judgment
Joaquim de Melo Freitas Square (End)	'*Obelisk of Liberty*'; '*Arcos Fountain*'; '*Former Ala Pharmacy*'	Final reflection on the square; Urban Memory and Identity	Experience synthesis; place re-signification (questionnaire-answering)	Reflecting on changes in perception of the square	Reflective thinking; valuing sustainability	Reflective synthesis

This structured overview reinforces how each MARG segment was designed to activate sustainability competences through contextualized, multimodal, and interdisciplinary learning. The deliberate recurrence of '*Joaquim de Melo Freitas Square*' as both the start and ending point exemplifies a pedagogical spiral model, in which learners revisit the same space with heightened awareness, deeper emotional engagement, and critical reflection [41]. This place-based approach supports situated learning processes, fostering identity construction, civic agency, and sustainability-oriented thinking in alignment with the GreenComp framework.

Pownall and colleagues [41] identified three critical success factors: learning outcomes, usability, and motivational appeal. These must be aligned with curricular goals and cross-disciplinary integration to be formally adopted [42].

The game design follows human-centered design principles, emphasizing intuitive navigation, affective interaction, and cognitive immersion, which are foundational to a positive player experience in AR-enhanced learning environments [7,22,23].

This validation ensured both ecological validity, by using real-world contexts, and pedagogical reliability, through alignment with sustainability competences and curricular objectives. Moreover, it prepares the ground for follow-up studies involving students in classroom- and field-based implementations. To further contextualize this validation strategy, Table 2 offers a comparative overview of selected AR-based serious games in heritage education. While most studies prioritize students' participation and focus primarily on usability or content knowledge acquisition, the present research adopts a markedly different approach by placing teachers, rather than students, at the center of the validation process. In contrast with existing studies that validate games post hoc with students, this study foregrounds teachers' insight in the pre-implementation phase, thereby addressing a critical gap in competence-based serious game design. This teacher-first strategy not only enhances curricular alignment, but also anticipates implementation challenges from the perspective of real classroom practitioners.

This approach addresses persistent critiques in the literature: namely, many serious games lack meaningful integration with pedagogical frameworks [43] and often disregard teachers' perspectives in both the design and evaluation phases [44]. By focusing on sustainability competences and using teachers as primary validators, the *Art Nouveau Path* bridges this gap, demonstrating how MARGs can be rigorously aligned with competence-based education goals.

Table 2. Comparative overview of AR-based serious games in heritage education.

Study	Audience	Validation Strategy	Educational Focus	Competence Framework	N	Notes
Bekas & Xinogalos [45]	Students (aged 10–14)	Pre/post-test, SUS, interview	Ancient Greek history	Not specified	129	Escape room and trivia AR game
Chiang et al. [18]	University students	Comparison (on-site vs. off-site), *t*-tests	Cultural heritage of Taiwan	Not specified	104	Compared learning motivation and satisfaction in two settings
Kleftodimos et al. [19]	K–12 students	Survey (challenge, reuse, interaction) and SEM	Local heritage and sustainability	Not specified	309	Validated challenge and reuse dimensions
This study (T1-VAL, T1-R)	Teachers	Simulation (T1-VAL), teachers' curricular review (T1-R)	Sustainability + heritage	GreenComp	33	Validated with teachers; implemented with more than 400 students (data not analyzed in this paper)

This comparative analysis highlights how the project bridges pedagogical design and structured validation, integrating multilayered architecture into a coherent process of development and implementation. While this paper focuses on the teacher validation phase, the *Art Nouveau Path* was subsequently implemented with over 400 students who participated in a longitudinal study with three distinct data collection moments (pre-test, post-test, and follow-up). Since student responses were collected anonymously, the data were treated as repeated cross-sectional samples. The analysis of these results, particularly regarding learning impact and the development of sustainability competences, will be presented in future publications.

To further clarify the structural logic of the game design and its validation process, Figure 9 presents the multilayered pedagogical model of the *Art Nouveau Path*, based on a six-layer framework. This enhanced model conveys the epistemological robustness of the approach, emphasizing the importance of co-design, iterative refinement, and educational implementation following the game's validation.

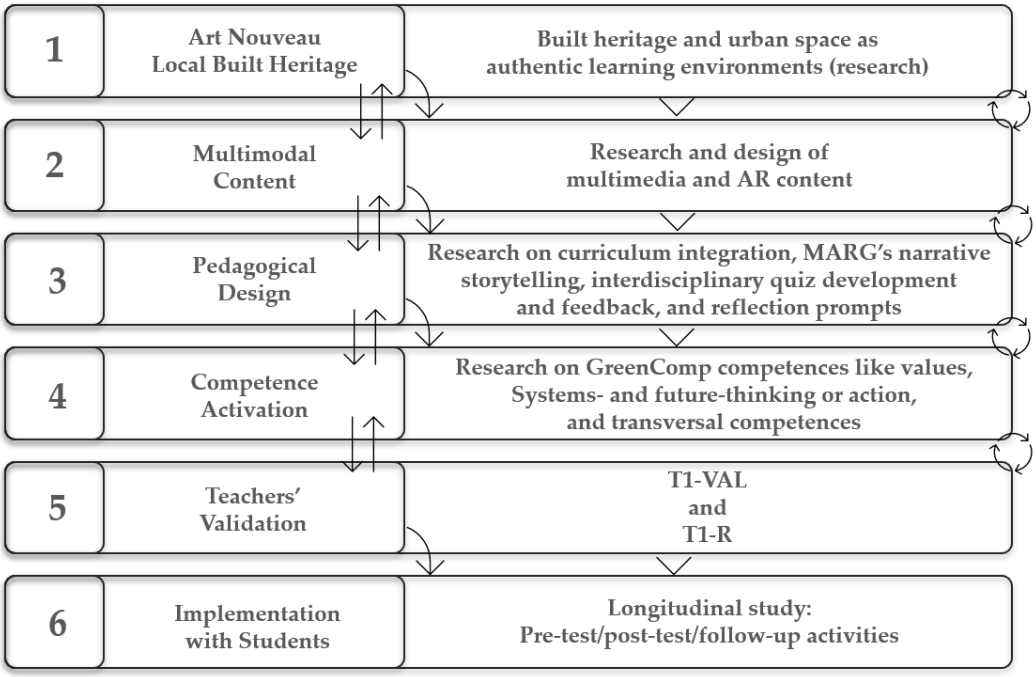

Figure 9. Multilayered pedagogical model of the *Art Nouveau Path* (designed by the first author).

The model illustrates how the game's design is deeply rooted in contextual heritage and sustainability education. Each layer contributes to the integration of real-world environments, immersive technologies, pedagogical strategies, and competence activation in alignment with the GreenComp framework. As such, the game is positioned not only as a digital learning tool, but also as an artifact of participatory and context-aware educational innovation.

The pedagogical model that supports the *Art Nouveau Path* is structured into six interdependent layers:

1. Local Built Heritage: based on the historical urban environment of Aveiro, which provides the real-world setting for the game.
2. Digital Content: includes AR markers, multimodal multimedia, and interactive elements that connect players to space through technology.
3. Pedagogical Design: features narrative tasks, reflection prompts, and interdisciplinary challenges to guide learning.

4. Competence Activation: engages players in applying GreenComp-based KSA to real sustainability issues.
5. Validation: informed by teacher feedback.
6. Implementation: application of the final version of the game in an authentic educational setting.

This layered framework serves both as a design structure and as an analytical lens for future implementations. It exemplifies how mobile AR serious games can transcend content transmission and foster emotionally resonant, situated, and interdisciplinary learning. As recent reviews emphasize, the alignment between immersive technologies, pedagogical structures, and sustainability competence frameworks remains rare, yet is essential for effective EDS [43,44].

The subsequent section details the methodological design that structured the teacher validation phase of the *Art Nouveau Path* MARG.

3. Materials and Methods

3.1. Research Design and Methodological Alignment

This study adopts a qualitative case study design informed by the principles of DBR [39,40], with a specific focus on the empirical validation phase of the *Art Nouveau Path* MARG. While the broader development of this MARG involved iterative refinement of its pedagogical, technological, and content elements, this paper addresses the empirical validation phase with teachers (T1-VAL and T1-R).

This strategy aligns with current standards in serious game research and ESD, which emphasize the integration of pedagogical coherence with competence-oriented frameworks, such as GreenComp, and the importance of involving teachers in the validation process [43,44].

The aim of this validation phase was to assess how a mobile AR experience designed around cultural heritage can support the development of sustainability competences through multimodal and situated learning. The empirical work was conducted through two interlinked activities: a training workshop with 30 in-service teachers (T1-VAL), and a curricular review conducted by three teachers from distinct disciplinary areas (T1-R). Together, these phases sought to examine the game's pedagogical alignment, curricular relevance, and educational usability prior to student implementation.

3.2. Summary of Art Nouveau Path Context and Development

The *Art Nouveau Path* was developed between October 2023 to December 2024, as an MARG supported by the [name] Project digital solutions. This Research and Development project is based at the University of Aveiro.

Drawing upon DBR principles, it supports iterative design, stakeholder feedback, and real-world testing across three essential phases: (a) exploratory fieldwork and content research; (b) multimodal media development, including AR and multimedia content, and prototype testing; and (c) pedagogical validation. Eight Art Nouveau buildings in Aveiro were selected as points of interest based on their architectural, historical, civic, and local value. Each location was conceptually linked to sustainability-related themes drawn from the GreenComp framework [20], such as systems thinking, responsibility, and future-oriented action. The final game version consists of 36 quiz-type questions, triggered by visual markers placed at specific built heritage points of interest. These challenges combine augmented reality elements, video and audio resources, historical overlays, narrative prompts, and immediate feedback.

The learning experience is structured as a progression flow across thematic, cognitive, and AR content complexity.

All multimodal media and educational resource content was produced by the first author, the game's lead researcher, using archives, academic sources, and community-contributed materials.

The design process was ethically grounded in principles of historical accuracy, cultural sensitivity, and accessibility.

This MARG's core features include the following:

a. Narrative storytelling linked to local, contextualized history and sustainability themes;
b. AR content triggered by architectural details used as natural markers;
c. Multimedia elements, including videos, audio narration, and 3D overlays;
d. Reflective and challenging quiz-type questions, each framed by robust introductions and supported by informative feedback;
e. A progression-based game narrative designed to activate and align with selected GreenComp sustainability competences.

Figure 10 illustrates the game's development process, structured into iterative validation stages and accompanied by a detailed explanation. This comprehensive framework covers all key phases, from the initial design and prototyping to the curricular review and the teacher training session.

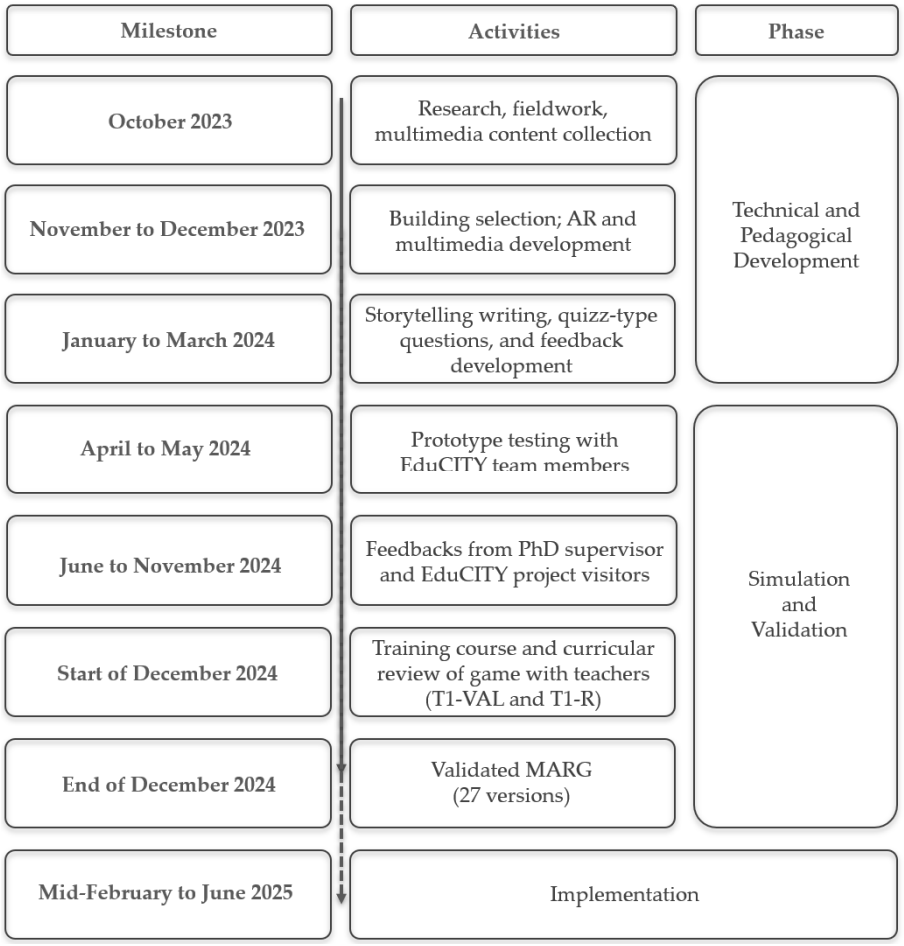

Figure 10. Timeline of game development and iterative validation process (created by the first author).

3.3. Participants and Ethical Considerations

The T1-VAL cohort consisted of 30 in-service teachers (17 female, 13 male) who willingly participated in the research. The participants granted informed consent, and no personally identifiable or sensitive information was gathered.

In addition, a second group of 3 teachers with disciplinary expertise in History, Natural Sciences, and Visual Arts/Citizenship participated voluntarily in the MARG's curricular review (T1-R).

All participants were from the central region of Portugal, and their disciplinary backgrounds spanned the Humanities, Sciences, and Arts, among other areas such as Civic and Citizenship Education, enabling a multi-perspectival analysis of the *Art Nouveau Path*'s interdisciplinary potential and curricular applicability.

Each procedure was carried out in accordance with the ethical standards defined by the University of Aveiro, and fulfilled the General Data Protection Regulation.

3.4. Teacher Validation Training Course (T1-VAL)

The teachers' validation was conducted in December 2024 during a training course titled "*Art Nouveau Path Workshop*". This training course structure was informed by the literature [46]. Although originally intended for on-site implementation, the workshop was conducted in a classroom setting due to weather constraints. Nevertheless, the simulation preserved the full design, sequence, and multimodal content of the eight-point urban path.

The training course participants engaged with the following:

a. A printed booklet containing the narrative structure, historical context, and additional content;
b. Video recordings and/or images of the path and gameplay mechanics (using a preliminary version of the MARG in the EduCITY app) presented during the training course;
c. Full access to multimodal media content and quiz functionalities (also by using the preliminary version of the MARG in the EduCITY app) (Figure 11).

Figure 11. The printed AR marker used in the "*Art Nouveau Path Workshop*", and EduCITY's smartphones.

Although this setup did not allow for full mobile spatial interaction, all activities conducted, such as group work, simulated the actual game dynamics. To ensure consistent experience across participant groups, the project's smartphones were used throughout the session.

This setting provided both ecological and technological fidelity, enabling teachers to interact with the same tools and content later used by students, and to offer informed feedback based on authentic gameplay conditions.

At the end of the session, teachers completed the questionnaire (available at https://doi.org/10.5281/zenodo.15916129).

3.5. Curricular Review (T1-R)

In parallel with the T1-VAL validation workshop, a targeted curricular review was conducted with 3 in-service teachers, selected for their disciplinary expertise in History, Natural Sciences, and Visual Arts/Citizenship Education. These participants, referred to as the T1-R group, did not engage in the gameplay simulation. Instead, they were invited to conduct an analysis of the game's structure, content, and curricular value through a structured rubric (available at: https://doi.org/10.5281/zenodo.15917417).

The rubric covered key dimensions of curricular alignment, including pedagogical soundness, cognitive appropriateness for the intended grade level, integration of sustainability themes, and potential for cross-disciplinary use. Each teacher received the complete narrative and question flow, multimedia resources, AR marker samples, and the printed booklet used in the teacher's training course.

Their analysis provided an in-depth appraisal of how the *Art Nouveau Path* MARG supports formal learning goals within their subject areas, and how it aligns with national curriculum standards and sustainability competences. Their feedback was essential in identifying opportunities for refinement, particularly in terminology precision, conceptual scaffolding, and the sequencing of disciplinary knowledge.

3.6. Data Collection Instruments

In this study, empirical data were collected using two instruments: (a) a post-game questionnaire completed by T1-VAL participants, and (b) a structured rubric completed by the 3 additional teachers (T1-R).

3.6.1. Post-Game Questionnaire (T1-VAL)

The post-game questionnaire (available at: https://doi.org/10.5281/zenodo.15916129) was developed to evaluate participants' perceptions of both the *Art Nouveau Path* MARG and the teacher training workshop, focusing on pedagogical relevance, usability, and applicability within sustainability education. The design of the instrument was grounded in established frameworks for evaluating serious games and competence-based learning environments [21,23,36,41], and was informed by mixed-methods educational research [47,48]. Its structure was aligned with the GreenComp framework [20], ensuring conceptual coherence in the evaluation of sustainability competences.

The questionnaire was structured into five sections, combining both quantitative and qualitative formats to capture a comprehensive range of participant insights:

1. Section A focused on participants' initial familiarity with core concepts such as built heritage, sustainability, and competences for sustainability. This section included closed-ended items with multiple response options (like *Yes*, *No*, *Not sure*, or *Other*), allowing respondents to express uncertainty or specify prior training experiences. These items aimed to establish a baseline of conceptual awareness and previous exposure to relevant educational topics.

2. Section B comprised 18 Likert-scale items, each rated on a six-point scale ranging from 1 ("*Don't agree*") to 6 ("*Agree*"). An even-numbered scale was intentionally used to prevent neutral responses and encourage more decisive evaluative positioning [49]. These items were grouped into three analytical domains: a) Heritage and Sustainability, addressing understanding of built heritage, its educational potential, and its link to sustainability competences such as cultural awareness and systems thinking; b) the *Art Nouveau Path* MARG, evaluating the game's interdisciplinarity, critical thinking value, digital engagement, and perceived usability in formal and informal learning settings; and c) Workshop and Methodology, assessing the structure, clarity, and relevance of the workshop, as well as participants' motivation and affective engagement.
3. Section C included seven closed-ended items designed to assess the applicability of the game and workshop in professional and educational contexts, as well as participants' familiarity with the GreenComp framework and the identification of specific sustainability competences. While most items followed a dichotomous (*Yes*/*No*) format, some also included additional options such as Not sure or Other, to accommodate partial familiarity or ambiguity in responses.
4. Section D consisted of six open-ended prompts encouraging participants to reflect more deeply on the use of augmented reality, the design and structure of the game, its educational value, and possible improvements for future iterations. These qualitative responses provided rich insights into user experience, engagement, and critical feedback.
5. Section E gathered anonymized demographic and disciplinary information, including age range and scientific teaching area, allowing for a broader contextualization of participant perspectives across their own backgrounds.

By combining scaled responses with narrative reflections and closed-ended answers, the questionnaire supported a triangulated and multidimensional analysis of participants' engagement with the Art Nouveau Path. Its combination of different answer typologies was aligned with study's mixed-method design, sustainability education goals, and the MARG's perceived value for teacher professional development.

3.6.2. Teachers' Curriculum Validation (T1-R)

As part of the iterative refinement phase of the DBR process, 3 teachers conducted a structured review of the game prototype. They represented three essential curricular domains relevant to the *Art Nouveau Path* experience: History, Natural Sciences, Visual Arts, and Citizenship Education. Each teacher was given access to all the game's content, including location-based triggers, multimodal media, AR content, and quiz materials. All of this was supported by the preliminary version of the *Art Nouveau Path* within the EduCITY app. This review process was conducted individually and asynchronously.

The rubric addressed six key dimensions:

1. The alignment of the game's content with formal curricular goals;
2. Its potential for interdisciplinary articulation across school subjects;
3. Its capacity to promote critical thinking and student reflection;
4. Its contribution to the development of observation and analytical skills;
5. The application or reinforcement of subject-specific concepts and competences;
6. The cognitive and age-appropriateness of the game for learners at the lower and upper secondary levels.

The process was grounded in instructional design principles and sustainability education frameworks, including GreenComp [20]. This approach was aligned with the principles of '*Understanding by design*' [50], which emphasize backward planning and inten-

tional learning design. Teachers were invited to reflect not only on curricular alignment, but also on the relevance and complexity of the content and the coherence of the overall learning pathway. Their individual responses were returned in written form and later analyzed using thematic synthesis [51]. Although this review was conducted independently of the T1-VAL workshop, it was integrated into the final iteration of the DBR cycle to inform refinements to phrasing, scaffolding, and competence mapping.

This triangulated perspective contributed to the validity of the evaluation protocol and ensured that the *Art Nouveau Path* was pedagogically sound and aligned with formal educational standards and sustainability competences.

3.7. Data Analysis Procedures

The quantitative data collected through the T1-VAL post-game questionnaire were analyzed using descriptive statistics, including measures of central tendency (means), dispersion (standard deviations), and frequency distributions. This analysis offered a structured overview of participants' perceptions across key dimensions, including competence activation, interdisciplinarity, emotional engagement, and curricular relevance.

The qualitative data from the open-ended questionnaire responses and teachers' rubrics (T1-R) were examined through thematic analysis, following Braun and Clarke's six-phase framework [51].

This combined approach provided a triangulated and multifaceted understanding of participants' perceptions, emotional reactions, and interpretations of the game's pedagogical value.

3.8. Validity, Reliability, and Methodological Considerations

As a concluding methodological reflection, the validation process was supported by a combination of strategies aimed at ensuring ecological fidelity, curricular alignment, and analytical robustness. Although the workshop was conducted indoors due to weather constraints, the full gameplay sequence was preserved through printed AR markers, project smartphones, and video walkthroughs. This setup enabled participants to interact with all core components of the *Art Nouveau Path* experience, ensuring a high degree of multimodal and spatial fidelity.

Pedagogical coherence was further reinforced by aligning the game's structure and content with the GreenComp framework [20], which guided the integration of sustainability competences across all tasks. The involvement of teachers from diverse disciplinary backgrounds ensured that cognitive demands, curricular relevance, and interdisciplinary articulation were thoroughly addressed.

Methodological triangulation was achieved through the integration of two complementary data sources: the T1-VAL post-game questionnaire and the teachers' curricular review (T1-R). This mixed-methods approach allowed for a multidimensional analysis of the game's educational value, based on both experiential and curricular criteria.

This approach is synthesized in Table 3, which maps the instruments used, the data types collected, the analytical approaches employed, and the learning dimensions explored.

These combined strategies facilitated a rich, layered interpretation of both cognitive and affective learning dimensions, thereby enhancing construct validity and interpretive robustness [47,48], while also providing a solid methodological foundation for the analysis presented in the next section. The following results examine how participating teachers perceived the *Art Nouveau Path* in terms of its educational potential, interdisciplinary relevance, and alignment with sustainability competences.

Table 3. Triangulation matrix summarizing instruments, data types, analysis methods, and learning dimensions in the validation phase.

Instrument	Data Type	Analysis Method	Learning Dimension
T1-VAL Questionnaire (Likert Items)	Quantitative	Descriptive statistics (mean, standard deviation, and percentage agreement)	Cognitive, affective, pedagogical alignment
T1-VAL Questionnaire (Dichotomous Items)	Quantitative	Frequency analysis	Applicability, usability
T1-VAL Questionnaire (Open-ended Items)	Qualitative	Reflexive thematic analysis [51]	Affective engagement, design suggestions
T1-R Curricular Review Rubric	Qualitative	Thematic synthesis using structured categories	Curricular coherence, cognitive depth

4. Pedagogical Validation of the Art Nouveau Path

This section presents the findings of the *Art Nouveau Path* validation with teachers. This validation was based on a triangulated analysis combining quantitative feedback, open-ended reflections (T1-VAL) and curricular review (T1-R). The findings are structured into four interrelated dimensions: (1) conceptual and affective engagement, (2) pedagogical value and interdisciplinarity, (3) professional applicability and curricular relevance, and (4) improvement suggestions and feedback. All data links are available in Appendix A.

Table 4 provides a comprehensive synthesis of the validation outcomes, integrating quantitative indicators, emergent qualitative insights, and curricular review highlights.

Table 4. Summary of triangulated validation outcomes of the Art Nouveau Path.

Dimension	Quantitative Evidence	Emerging Qualitative Themes [51]	Contributions from Teachers' Curricular Review (T1-R)
Conceptual and Affective Engagement	M = 5.60 (SD = 0.61)	Emotional resonance; rediscovery of urban space through AR and storytelling	Strong affective activation; meaningful heritage engagement via multimodal immersion
Pedagogical Value and Interdisciplinarity	M = 5.50 (SD = 0.68)	Interdisciplinary applicability; alignment with values-based learning	Cross-curricular coherence; integration of systems thinking and futures literacy competences
Curricular Relevance and Transferability	M = 5.37 (SD = 0.82); 90% would recommend use	Classroom adaptability; curricular alignment; use in formal and informal settings	Supports curricular objectives; promotes cognitive complexity; adaptable to varied contexts
Improvement Suggestions and Future Refinements	–	Requests for greater competence visibility, simpler interface, and offline options	Recommendations for metacognitive scaffolding, content modularity, and teacher mediation tools

This table provides a concise synthesis of the triangulated validation data (https://doi.org/10.5281/zenodo.15917291). The following subsections expand upon the findings presented above, offering a deeper interpretation of the data in relation to the theoretical framework and research aims of this study.

4.1. Conceptual and Affective Engagement

The results indicate a strong conceptual and emotional resonance with the game's thematic framework. Quantitative data show that participants reported high levels of understanding of heritage and sustainability (M = 5.43; SD = 0.73), and even higher levels of emotional and motivational engagement (M = 5.60; SD = 0.61). These findings suggest that the game successfully mobilized affective and cognitive dimensions [52,53], aligning with the GreenComp framework's values-based area [20].

Qualitative responses reinforce this impression. Participants described the game as an "eye-opener" in relation to their own city, with one teacher noting, "I walk these streets every day, but I never really saw the buildings until now. The game made me look differently" (T08). This affective activation aligns with recent scholarship on place-based and embodied learning [29,35,53], particularly when mediated by immersive technologies. The narrative structure, based on the triad of '*Urban Memory and Identity*', '*Cultural Esthetics and Nature*', and '*Sustainability and Action*', was perceived as enabling deeper reflection and situated engagement with the urban environment. In doing so, this MARG responds to calls for educational experiences that foster civic awareness and environmental consciousness through affective anchoring [36,43,52,53].

4.2. Pedagogical Value and Interdisciplinarity

Teachers rated the game highly for its pedagogical design and cross-curricular relevance (M = 5.50; SD = 0.68). Feedback highlighted clear connections to a wide range of curricular areas, including History, Visual Arts, Natural Sciences, Mathematics, and Citizenship Education. This interdisciplinary relevance supports the notion that mobile AR experiences, when grounded in local heritage, can serve as integrative educational platforms [27,31].

Participants emphasized the game's ability to promote analytical observation, critical interpretation, and values-based discussion [54]. As one teacher observed, "This is not a simple guided tour. It's a reflective learning experience that invites observation, analysis, and values exploration" (T12). The game's curricular value reviewers (T1-R) also confirmed that the game fosters competences related to systems thinking, futures literacy, and civic agency, in line with GreenComp framework [20]. Through contextualized challenges and visual narratives, abstract sustainability competences are translated into concrete actions, reinforcing arguments from recent research on competence-based digital learning [34,37].

4.3. Curricular Applicability and Identified Implementation Challenges

The game was perceived as highly adaptable to both formal and informal educational contexts, with 90% of teachers stating that they would recommend its use and 87% endorsing its potential for extracurricular implementation. These high levels of approval support the game's alignment with curricular flexibility and competence-oriented pedagogy [21].

However, implementation challenges were also identified. The most frequently reported issue was limited access to AR-compatible devices, a concern particularly relevant in under-resourced schools. Participants also noted the need for alternative versions of the game (like printable formats, or boardgames) and for subject-specific teacher guides to support curricular integration. These limitations resonate with broader debates on equitable access to digital educational resources [26].

The expert reviewers echoed these concerns, recommending differentiated resources by age and subject area. They also advocated modular content, scaffolded instructions, and offline options to ensure inclusivity. These suggestions are aligned with best practices for designing digital learning tools within diverse educational ecosystems [34,54].

5. Results

This section outlines the results obtained from the empirical evaluation of the *Art Nouveau Path* MARG. This study addressed the following interconnected research questions:

1. How do multimodal and location-based interactions within the *Art Nouveau Path* MARG influence learner engagement and player experience?
2. How can mobile AR serious games support the development of sustainability competences through context-aware educational interactions?

Findings from the teacher validation workshop (T1-VAL), analyzed individually in Section A (https://doi.org/10.5281/zenodo.15916828, Section B https://doi.org/10.5281/zenodo.15917001, Section C https://doi.org/10.5281/zenodo.15917114 and Section D https://doi.org/10.5281/zenodo.15917192), and the curricular review (T1-R) (https://doi.org/10.5281/zenodo.15917517) provide converging evidence that this MARG activates meaningful forms of cognitive, emotional, and professional engagement.

5.1. Engagement and User Experience Through Multimodal, Situated Learning

The first research question concerns the impact of the game's multimodal and context-aware design on user engagement. Quantitative data reveal high emotional and motivational engagement (M = 5.60), along with a strong conceptual grasp of the connection between built heritage and sustainability (M = 5.43).

Participants frequently highlighted the affective impact of the experience. As one teacher noted, "The game makes the city come alive for students" (T08), while another stated, "I will never look at some of these buildings the same way again" (T15). These reactions exemplify the activation of place-mediated memory [11] and the re-signification of urban space as theorized by Choay [12].

The use of augmented reality was described as "transformative for learning" (T03) and "capable of capturing even students with low attention spans" (T21). Such responses reinforce the idea that AR can foster situated learning through embodied interaction [5,7,26], aligning with transformative learning theories [24,25].

Furthermore, the game's structure supported emotional resonance with heritage, consistent with the GreenComp emphasis on values engagement [20]. Several teachers remarked on the emotional appeal of specific locations, such as "the photo of the 1938 floods made me reflect on what my grandparents lived through" (T11), confirming the role of heritage as an affective entry point into sustainability discussions [52–55].

5.2. Sustainability Competence Development Through Game-Based Heritage Education

The second research question addresses the game's capacity to activate sustainability competences. Teachers and experts confirmed that the game successfully integrates GreenComp dimensions, particularly systems thinking, futures literacy, and civic engagement.

One teacher commented, "The tasks link history with present challenges, students can really see the connections" (T02), while another stated, "I used to teach about pollution abstractly. Now I can show them actual buildings and discuss acid rain with meaning" (T27). This illustrates how place-based AR can contextualize abstract sustainability issues [15,18,19,30].

The three narrative pillars, '*Urban Memory and Identity*', '*Cultural Esthetics and Nature*', and '*Sustainability and Action*', offered a cohesive structure that enabled interdisciplinary exploration. As one participant observed, "It's not just about architecture, it is about values, history, and the future" (T12). This aligns with the literature advocating for heritage learning as a powerful catalyst for critical thinking and civic awareness [36–38,53–55].

Expert reviewers further confirmed the game's alignment with multiple literacy domains and national curriculum standards. This underscores the value of MARGs as tools

for competence-based education, provided that they are contextually grounded and pedagogically framed [18,34,35].

5.3. Addressing Challenges: Accessibility, Transferability, and Inclusion

Despite overall positive feedback, teachers raised important challenges regarding access and equity. One teacher explained, "Not all schools have devices that can run AR smoothly" (T06), pointing to the need for printable, low-tech alternatives, an issue echoed in broader discussions on digital equity [6,46,55].

Others highlighted inclusion needs: "Some students would need audio descriptions or simpler language to follow all tasks" (T25). These observations are consistent with current critiques of educational game design for not adequately addressing diverse learning needs [35,56].

Several participants also called for clearer visibility of the GreenComp competences during gameplay. As one put it, "It's a great game, but students need help understanding what they're learning in terms of sustainability" (T10). This aligns with research advocating for stronger metacognitive scaffolding in competence-based learning [21].

5.4. Implications for Teacher Practice and Curriculum Integration

Finally, the game was seen as highly relevant to teaching practice. Teachers expressed intent to use it in interdisciplinary projects: "It works beautifully across History, Arts, and Citizenship" (T09). Others noted its suitability for project-based learning and extracurricular activities.

This confirms the importance of involving teachers in the co-validation of digital learning tools [39,40]. The structured validation prior to student implementation strengthens the pedagogical soundness of the resource and contributes to a more grounded integration into formal and informal learning scenarios.

The use of GreenComp as a reference framework facilitated curricular articulation across disciplines and school levels. Teachers welcomed the opportunity to align competences with concrete tasks, a process that promotes greater coherence between pedagogical intentions and digital innovation [20,21]. In summary, the game's capacity to support sustainability learning through affective, interdisciplinary, and place-based engagement has been demonstrated. The following section concludes the paper by outlining the study's main contributions, acknowledging its limitations, and suggesting pathways for future research and practical application in both formal and non-formal learning contexts. These and other conclusions, as well as limitations and future work, are presented in the next and last section.

6. Conclusions, Limitations, and Future Paths

The present study examined teachers' validation of the *Art Nouveau Path* MARG, developed to activate sustainability competences through cultural heritage engagement.

6.1. Main Findings

Three major contributions emerge from the findings. First, the game demonstrated the ability to engage teachers through affective, spatial, and multimodal interactions. Participants reported high levels of motivation, curiosity, and personal resonance, often citing the emotional connection with local heritage sites as a driver of reflection. This aligns with the existing literature on the role of emotion in AR-mediated learning, and supports the value of place-based narratives in competence activation.

Second, the Art Nouveau Path successfully addressed several GreenComp dimensions, particularly systems thinking, values-based engagement, and futures literacy. Through architectural details, historical episodes, and guided questions, teachers were able to discuss

complex sustainability issues using tangible, local references. Expert reviewers affirmed the game's curricular coherence and its potential to support interdisciplinary teaching across areas such as Visual Arts, History, Citizenship Education, and Natural Sciences.

Third, the game revealed a high degree of transferability and adaptability. Teachers from diverse disciplinary backgrounds found relevant entry points to integrate the game into their curricula. The modular structure and embedded reflection tasks contributed to its pedagogical versatility, reinforcing its suitability for both formal and non-formal learning settings, including project-based and competence-based approaches.

6.2. Pedagogical and Practical Implications

The findings support several actionable recommendations for teachers, instructional designers, and policymakers working at the intersection of heritage, sustainability, and digital innovation.

First, pedagogical scaffolding is essential. While the game functions as a self-contained experience, its impact is amplified when followed by structured activities such as thematic debates, collaborative projects, or guided reflections. These extensions support deeper learning, allowing students to apply sustainability competences and make connections between heritage, values, and action.

Second, curricular alignment tools are critical for widespread adoption. Several teachers, especially from STEAM areas, requested clearer mapping of game content to national curriculum standards. Providing explicit documentation of GreenComp dimensions, lesson plan templates, and assessment rubrics can increase teacher confidence and integration success.

Third, inclusive design must guide future iterations. Although the game was designed to run on mobile devices using the EduCITY app, additional formats (printable guides or classroom-only simulations) are needed to ensure accessibility in under-resourced settings. Equity in digital learning requires flexibility, especially when deploying technology-enhanced heritage education.

Fourth, professional development remains a priority. Teachers in the study valued the hands-on experience, but expressed a need for continued pedagogical support. Co-design sessions, interdisciplinary learning communities, and peer-led training can empower teachers to adopt mobile AR in meaningful and sustainable ways.

6.3. Methodological Contributions and Limitations

Methodologically, this study contributes to the validation of serious educational games through a mixed-methods design combining quantitative feedback, qualitative thematic analysis, and curricular review. This triangulation ensured ecological, curricular, and experiential validity, responding to calls in the literature for multidimensional evaluation of learning technologies.

However, limitations must be acknowledged. The implementation was based on a simulated gameplay in a controlled space, which, while pedagogically effective, limited the full embodiment of location-based learning. Although AR markers and visual simulations preserved spatial immersion to an extent, future work did explore real-world implementation.

The sample was composed entirely of in-service teachers, potentially introducing bias toward innovation and sustainability education. While this aligns with the study's exploratory goals, the absence of student perspectives in this phase limits, at this stage, conclusions regarding learning outcomes and classroom dynamics.

Furthermore, some disciplinary integration challenges were noted. Participants from Mathematics and Natural Sciences backgrounds expressed uncertainty about how to embed

the game into their curricula without additional guidance or task adaptation. These insights suggest the need for targeted support materials.

Reflections on the Simulation-Based Evaluation

The use of a simulation-based implementation, necessitated by logistical constraints, offered an opportunity to evaluate the pedagogical affordances of the game in a controlled yet authentic learning context. Teachers interacted with printed AR markers, watched videos of the physical locations, and engaged with the full narrative structure of the game. Although this format did not fully replicate the embodied spatiality of in situ AR gameplay, it preserved essential features of place-based learning and emotional immersion.

This approach aligns with recent studies suggesting that hybrid or simulated AR experiences can still foster affective and cognitive engagement when designed with authenticity and narrative coherence [19,52]. Moreover, the simulation created a shared reflective environment, prompting teachers to explore practical applications, such as using the game as a pre-visit tool or within blended learning scenarios.

These findings suggest that simulation-based methods may constitute a viable first step in the iterative development and evaluation of mobile AR learning tools. They allow for early-stage testing, broad teacher involvement, and contextual adaptation, factors essential to the success of innovative educational technologies.

6.4. Future Research Paths

Several pathways emerge for future research.

First, longitudinal studies are needed to assess the sustained impact of the game on competence development, including behavioral change, value internalization, and systems thinking over time. Pre-/post-/follow-up studies with students can provide insights into retention and transfer of learning.

Second, comparative studies between AR-enhanced and non-AR versions of the game would clarify the specific contribution of augmented spatiality and multimodal interaction to learning outcomes and motivation.

Third, the adaptability of the model to other cities and heritage contexts should be explored. Given its modular structure and geolocated logic, the *Art Nouveau Path* can be replicated or localized to other urban landscapes, enabling comparative research across socio-cultural settings.

Finally, future iterations of the game should adopt participatory co-design approaches, actively involving students in the creative process. This will aim to include students as both testers and authors of questions, or narrative contributors, which may enhance their sense of ownership, the major relevance of the game, and its learning impact.

6.5. Summary of Findings and Contributions

The Art Nouveau Path exemplifies how mobile augmented reality can transform built heritage into a living curriculum for sustainability. Rooted in local identity and aligned with the GreenComp framework, it bridges the cognitive and affective dimensions of education, fostering reflective, interdisciplinary, and values-based learning.

As educational systems seek to address the complexities of sustainability and digital transition, context-aware, emotionally engaging, and competence-oriented learning experiences are urgently needed. This study contributes to that agenda by demonstrating that heritage-based AR games can promote deeper civic engagement, critical reflection, and the development of future-ready learners.

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Abbreviations

The following abbreviations are used in this manuscript:

ESD	Education for Sustainable Development
KSA	Knowledge, Skills, and Attitudes
AR	Augmented Reality
MARG	Mobile Augmented Reality Game
DBR	Design-Based Research
EU	European Union
OECD	Organization for Economic Co-operation and Development
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization

Appendix A

All supporting materials related to the T1-VAL and T1-R phases, including questionnaires, summary analyses, and triangulated data, are available for consultation at the following Zenodo links:

T1-VAL Questionnaire: https://doi.org/10.5281/zenodo.15916129
T1-VAL—Summary A: https://doi.org/10.5281/zenodo.15916828
T1-VAL—Summary B: https://doi.org/10.5281/zenodo.15917001
T1-VAL—Summary C: https://doi.org/10.5281/zenodo.15917114
T1-VAL—Summary D: https://doi.org/10.5281/zenodo.15917192
T1-VAL—Triangulated Analysis: https://doi.org/10.5281/zenodo.15917291
T1-R Questions: https://doi.org/10.5281/zenodo.15917417
T1-R—Analysis Data: https://doi.org/10.5281/zenodo.15917517.

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