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The *Art Nouveau Path*: Integrating Cultural Heritage into a Mobile Augmented Reality Game to Promote Sustainability Competences Within a Digital Learning Ecosystem

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Abstract

The integration of sustainability competences into education presents significant challenges, particularly in embedding Education for Sustainable Development (ESD) into contextually relevant learning experiences. This study presents the design and validation of the *Art Nouveau Path*, a Mobile Augmented Reality Game (MARG) developed within the EduCITY ecosystem to foster competences, such as sustainability values, systems thinking, and future literacy. Grounded in the GreenComp framework and employing a Design-based Research (DBR) approach, the intervention was validated with 33 in-service teachers through a simulation-based workshop and a curricular review and complemented by a diagnostic questionnaire was administered to 221 students. This questionnaire (S1-PRE) provided the baseline data on sustainability awareness, digital readiness, and heritage-related learning interest. The teachers confirmed the MARG's curricular adequacy value and interdisciplinary potential, while the students' diagnostics revealed mixed conceptions; although 73.30% considered sustainability competences important, only 61.10% expressed interest in learning more about them. Also, 72.40% showed interest in learning about sustainability through local Art Nouveau heritage, and 79.60% considered the theme attractive, indicating potential for emotional and cognitive engagement. The *Art Nouveau Path* provides an exploratory and replicable model of curriculum-integrated ESD, connecting cultural heritage with competence-based learning for the operationalization of the GreenComp framework in support of SDG 4.7.

Keywords: Art Nouveau; sustainability competences; digital teaching and learning ecosystems (DTLEs); place-based learning; augmented reality; mobile learning; game-based learning

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1. Introduction

Education for Sustainable Development (ESD) is defined by the United Nations Educational, Scientific and Cultural Organization (UNESCO) [1] as the process that equips learners with knowledge, skills, values, and attitudes to act for environmental integrity, economic viability, and social justice, ensuring well-being for present and future generations. The ESD framework, as presented by the UNESCO [1], is fundamentally oriented towards empowering learners to operate sustainability transitions and fulfil Sustainable Development Goals (SDGs). This vision goes beyond content delivery, requiring the development of critical skills to engage with systemic complexity [2–4]. Furthermore, the curriculum should be meticulously structured to foster ethical standards and enable learners to address real-world challenges in a truly transformative approach [5].

Alongside this pedagogical transition towards competence-oriented education for sustainability (EfS), digital innovation has emerged as a significant catalyst for educational transformation, considering its potential to enhance accessibility, relevance, engagement, and inclusivity. Global reports and initiatives demonstrate that technology can improve learning outcomes, enable flexible delivery, and promote equity in various contexts [1,6]. However, despite the concurrent rise of ESD and educational technology, the two remain insufficiently integrated in educational practice. This is evident in practice, with the conventional approaches to sustainability education often being abstract and confined to the classroom, disconnected from students' daily lives.

Although competence-oriented frameworks such as GreenComp—the European Sustainability competences framework [2] have become important in defining the sustainability competences that learners require, they have not yet been widely implemented in digital and context-rich learning environments. This is particularly evident in attempts to encourage affective, inclusive, and place-based sustainability learning among younger students [7].

Mobile, location-based learning enhances student engagement, contextual awareness, and emotional connection to a place [8–10]. By anchoring learning in familiar environments, it promotes active and participatory experiences. Mobile Augmented Reality Games (MARGs) further this potential by turning urban spaces into interactive educational settings. When structured around meaningful narratives and game mechanics, MARGs have been shown to increase motivation, engagement, and knowledge retention [11].

Cultural heritage provides a powerful context for sustainability education, offering an interdisciplinary lens that integrates ecological, aesthetic, social, and historical dimensions. Recent research advocates for embedding heritage sites into immersive ESD experiences [12,13]. Learning in authentic environments using collaborative and inquiry-based methods has been shown to foster engagement and develop sustainability competences [14].

This study presents the *Art Nouveau Path*, a Mobile Augmented Reality Game (MARG) developed within the EduCITY Digital Teaching and Learning Environment (DTLE) (https://educity.web.ua.pt/) (accessed on 14 June 2025), aimed at lower and upper secondary school students. Implemented in Aveiro's Art Nouveau district, it comprises 36 quiz-based tasks linked to eight heritage Points of Interest (PIs). Each challenge connects sustainability themes, such as urban transformation, resource use, and intergenerational responsibility, with local heritage through multimodal and context-aware interactions, thereby connecting cultural heritage with contemporary sustainability issues. Figure 1 presents the full path connecting the eight PIs.

Integrating local built heritage into digital narratives via Augmented Reality (AR) and multimodal media promotes sustainability awareness through storytelling. Each PI-specific challenge follows a narrative arc that encourages close observation of Art Nouveau architecture, while fostering reflection on sustainability themes. The MARG is structured around the European GreenComp framework [2] and aligned with national curricula and local history, enhancing its interdisciplinary value.

The *Art Nouveau Path* was developed within the EduCITY DTLE. EduCITY provides the digital infrastructure and authoring tools to create AR-based learning experiences that treat the city as a living classroom, fostering immersive, place-based learning [15,16].

Figure 1. *Art Nouveau Path* map in EduCITY app (version 1.3) map (in-game screenshot, path, and 3 PIs).

Despite advances in educational AR and policy support for ESD, few empirical studies explore the intersection of heritage, mobile learning, AR, and competence-based approaches in real-world contexts [17]. Moreover, the existing methodologies rarely involve teachers in the co-design or validation of digital tools [18,19]. This study aims address these gaps by presenting the design and validation of a GreenComp-aligned MARG centered on Aveiro's Art Nouveau heritage. The study employed a Design-based Research (DBR) [20,21] approach with validation from 33 teachers. It was also undertaken a diagnostic questionnaire (S1-PRE) with 221 students to understand their self-perceptions of sustainability awareness and local Art Nouveau heritage.

The design process involved iterative input from thirty in-service teachers (T1-VAL) and three other teachers, subject specialists (T1-R), whose feedback guided the refinements. The intervention was then implemented with students in authentic settings.

As presented in Figure 2, the design and implementation of the *Art Nouveau Path* follows a multilayered pedagogical structure that consolidates heritage-based content, competence-driven learning strategies, and validated educational practices.

For instance, tasks based on water conservation relate to 'Acting for sustainability', while challenges regarding built heritage address 'Embodying sustainability values', previewing how GreenComp is operationalized in the MARG. The overarching goal of the *Art Nouveau Path* is to establish a replicable model for inclusive and engaging ESD by integrating GreenComp sustainability competencies into a significant local heritage narrative.

This approach aligns learning experiences with both the local context and international policy frameworks.

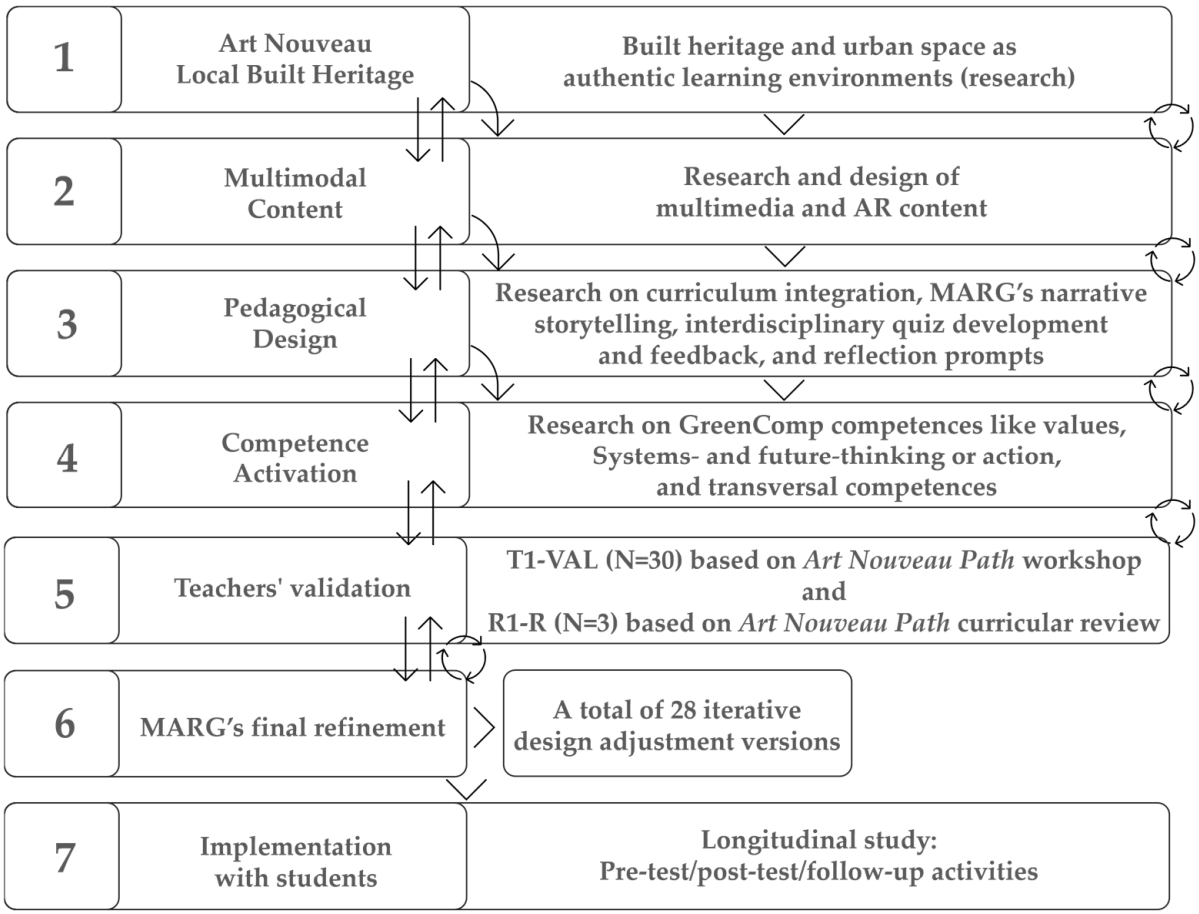

Figure 2. Multilayered pedagogical model of *Art Nouveau Path* MARG.

The following research questions (RQs) were formulated to guide this study: (RQ1) How does the *Art Nouveau Path* MARG foster the activation of sustainability competences in students? (RQ2) What are students' perceptions of the MARG's educational value, engagement, and usability in their urban environment? (RQ3) What design and pedagogical insights emerge from applying the GreenComp framework and a Design-based Research approach in developing an inclusive, competence-oriented AR learning experience?

This study contributes to the field of digital education for sustainability along two axes: (1) by outlining the conceptual foundations and design principles of the *Art Nouveau Path* MARG; and (2) by detailing the DBR process and presenting the initial empirical findings from its implementation. The results highlight the potential of combining MARGs and built heritage within DTLEs to foster inclusive, place-based, and competence-driven learning.

Following the introduction, Section 2 presents a narrative thematic review of the literature and theoretical frameworks. Section 3 describes the methodological design, including the context, the participants, the instruments, and the DBR approach. Section 4 reports the findings from teacher validation (T1-VAL and T1-R) and the student diagnostic phase (S1-PRE). Section 5 discusses the pedagogical and methodological implications of these results. The final section synthesizes the key contributions, identifies limitations, and suggests paths for future research.

2. Theoretical Framework

This section presents a narrative thematic literature review [22–24] grounded in established procedures for thematic synthesis [25,26]. The review applied both inductive and deductive coding techniques [25,26] to structure the theoretical framework across five domains: (1) ESD and SDG 4.7, (2) DTLEs, (3) AR and Mobile Games in ESD, (4) the GreenComp framework, and (5) built heritage as a pedagogical context. The searches were conducted in Scopus and Web of Science, complemented by exploratory scans in Google Scholar to capture the grey literature and institutional reports. The search period was April–May 2025, targeting works published between 2012 and 2024. Effective keyword combinations included *heritage AND sustainability competences*; *education for sustainable development AND augmented reality*; *digital teaching and learning ecosystems AND sustainability*; and *GreenComp AND education*. Direct searches using *Art Nouveau* mostly returned art-historical results and were excluded as irrelevant.

Studies were included if they (1) were peer-reviewed and indexed in Scopus or Web of Science, (2) explicitly addressed sustainability competences or competence-oriented education, and (3) connected to heritage-based, digital, or AR-mediated learning. The exclusion criteria comprised (1) studies focused only on technical aspects of AR without pedagogical framing, (2) heritage themes unrelated to education, (3) purely theoretical reflections lacking empirical or design-based components, and (4) duplicates or thematically irrelevant records.

The database search initially returned 48 records. After screening and excluding 31 items, the final set retained 17 peer-reviewed academic articles. The final corpus comprised thirty-seven sources organized into five categories: (1) seventeen academic articles [27–43] (peer-reviewed; detailed in Appendix A); (2) seven policy frameworks [1,2,44–49]; (3) three books [50–52]; (4) three authorship-related publications [53–55]; and (5) six previously used research sources [56–61].

A hybrid thematic analysis was undertaken, integrating inductive and deductive coding. Following Boyd [26], multiple reasoning modes were iteratively applied to ensure conceptual coherence across the five previously identified domains. The policy frameworks and the reference works grounded the analysis in internationally recognized sources, while the authorship-related publications secured continuity with prior research.

A detailed overview of the 17 peer-reviewed articles, including methodological focus, contexts, outcomes, and GreenComp/ESD domain alignment, is provided in Appendix A, which also shows that the corpus reveals a clear concentration of studies in AR- and game-mediated learning, while contributions on ESD policy enactment, DTLEs, and built-heritage contexts remain comparatively scarce. Most empirical works report short-term gains in knowledge, attitudes, or engagement, but only a minority explicitly operationalize sustainability competences or align outcomes with frameworks such as GreenComp. The conceptual and review papers provide valuable framing, yet seldom connect AR, heritage, and competence development within a single design. The references to GreenComp itself are marginal, with most studies relying on general ESD notions. These asymmetries substantiate the gap addressed by the present study: the systematic integration of built heritage, mobile AR, and competence-oriented ESD through GreenComp-aligned design and assessment.

The following subsections examine each of the five domains in turn, beginning with ESD and its integration within the broader framework of SDG 4.7.

2.1. ESD and SDG 4.7

ESD has emerged as a central paradigm for advancing sustainability competences, as explicitly recognized in the UNESCO framework [1,44] and operationalized in European

GreenComp [2]. Building on the UNESCO's vision, GreenComp translates this paradigm into a triadic model of Knowledge, Skills, and Attitudes (KSA), functioning as a holistic structure for competence development in sustainability-oriented education [2]. This articulation highlights ESD not only as a policy framework, but also as a pedagogical orientation that requires systemic, ethical, and transformative learning approaches.

As highlighted in SDG 4.7 [1], ESD extends well beyond environmental literacy to embrace global citizenship, social justice, and ethical responsibility. These dimensions provide the foundation for a community-oriented, value-driven educational system in both formal and informal settings, promoting the integration of sustainability competences into curriculum design and pedagogical strategies. Despite its theoretical foundations, however, a persistent implementation gap persists. Previous studies report that although ESD is widely endorsed in principle, its integration into curricula, teaching methods, and assessment frameworks is fragmented and inconsistent [27,42,43]. This gap is particularly evident in digital applications, where the emphasis often regards on technical proficiency rather than on transformative learning outcomes [27,28].

Some educational interventions have sought to address this gap by using arts, storytelling, and participatory projects regarding ESD [42,43]. While these approaches promote critical awareness and civic engagement, they seldom provide scalable models or robust guides for assessing competence development. Moreover, although affective engagement and learner agency are frequently emphasized as intended outcomes, few models explicitly connect these dimensions to structured framework as GreenComp [2], nor do they offer psychometric or methodological tools for validating sustainability competences.

The present study contributes to the literature by integrating the GreenComp framework with ESD principles in a game-based learning environment. The *Art Nouveau Path* integrates GreenComp [2] in two complementary ways: first, by offering an immersive, context-rich learning environment anchored in built heritage; and second, by employing a structured self-assessment tool, the GreenComp-Based Questionnaire (GCQuest) based on the '*Embodying Sustainability Values*' domain [53].

2.2. Digital Teaching and Learning Ecosystems (DTLEs)

DTLEs are interconnected environments that combine technological platforms, digital resources, pedagogical strategies, and human actors to support learning in dynamic, and adaptive ways [45,48]. They emphasize the integration of technology with pedagogy, ensuring that learning remains contextual, competence-oriented, and responsive to diverse learner needs.

In this study, DTLEs are conceptualized as a bridge between formal education and real-world complexity, promoting participatory and networked forms of learning. When intentionally designed, they may allow learners to connect formal-based knowledge with authentic contexts, thereby reinforcing the transformative ambitions of ESD.

DTLEs, particularly when combined with mobile and AR technologies, have demonstrated considerable potential for educational innovation [40,54]. However, the evidence suggests that their success depends less on technological novelty and more on pedagogical design, teacher mediation, and curricular alignment [34,41]. The effectiveness of a DTLE is therefore contingent on embedding competence frameworks and designing purposeful, contextually relevant activities. While most reviewed works emphasize the technical and motivational affordances of DTLEs, relatively few studies explicitly examine how such ecosystems can be structured to cultivate sustainability competences [34,35].

The EduCITY platform (https://educity.web.ua.pt) (accessed on 14 June 2025) exemplifies a DTLE designed around ESD and place-based learning. It provides both a technical infrastructure and an authoring environment to develop AR experiences such as the *Art*

Nouveau Path [12]. EduCITY also enables teachers, students, and communities to co-create mobile AR learning experiences, fostering scalability, local adaptability, and participatory innovation across diverse real-world contexts [10,54]. Its modular design facilitates the integration of AR and multimedia content into location-based learning, highlighting its potential for transferability to diverse geographical and social contexts.

Despite these opportunities, persistent challenges remain. These include infrastructural inequalities, insufficient teacher training, limited interdisciplinary collaboration, and the undervaluation of mobile technologies in formal education [40,41]. Moreover, there is an urgent need to move beyond rhetorical references to frameworks such as GreenComp [2], ensuring they are systematically embedded into the design, implementation, and assessment of DTLEs.

The *Art Nouveau Path* directly addresses these gaps by exemplifying a pedagogically grounded DTLE. Through GreenComp-aligned design and teacher-validated co-creation [55], this MARG demonstrates how digital tools can support situated, competence-based learning. Embedding GreenComp competences into a gamified, mobile environment that is rooted in students' everyday surroundings has proven effectiveness in fostering sustainability competences [27]. The iterative co-design process, validated through teacher participation [55], illustrates how technology can be aligned with purposeful pedagogy to foster sustainability competences in context-rich educational settings. Figure 3 illustrates this integration, presenting how the *Art Nouveau Path* operationalizes GreenComp through collaborative design and authentic contexts.

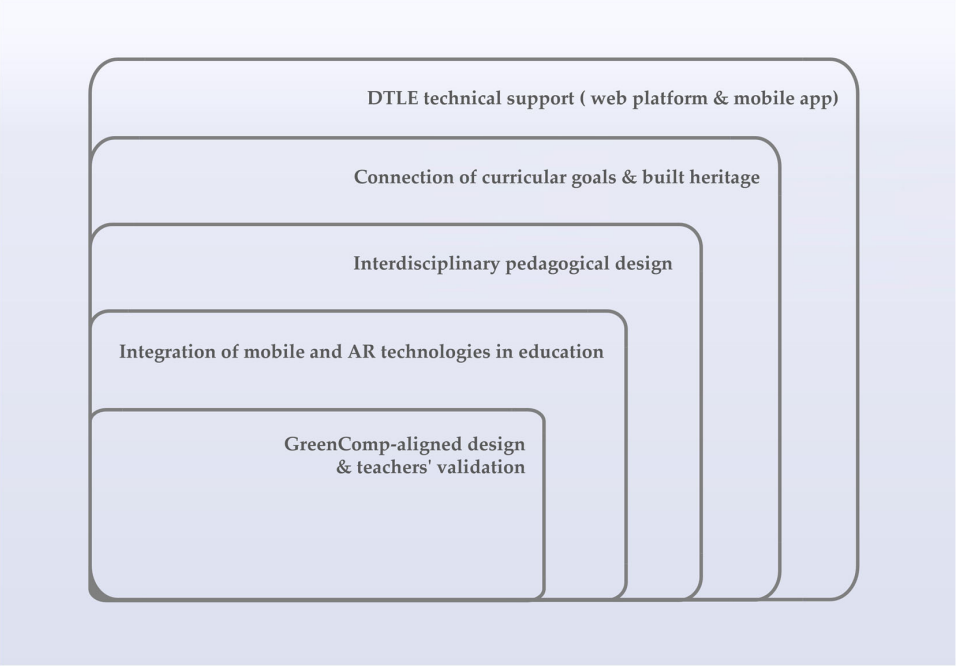

Figure 3. Structural integration of DTLE, curriculum, and GreenComp through teacher-validated co-design.

2.3. AR and Mobile Games in ESD

AR is increasingly recognized as a powerful educational tool, capable of fostering immersive, embodied, and context-sensitive learning experiences. Embedding digital information within physical environments supports the contextualization of abstract concepts and enhances both conceptual understanding and learner motivation [28,42,43]. These affordances are particularly relevant to ESD, which calls for active participation, critical reflection, and systems thinking [2].

Recent studies have documented a diverse range of AR applications in education, including enhanced textbooks, interactive museum experiences, and geolocated Mobile Games that foster spatial exploration and storytelling [10,37,40]. These examples highlight AR's capacity to link digital content with physical contexts, increasing learner engagement and extending opportunities for experiential learning.

In the field of sustainability education, AR has been valued for its ability to envision ecological processes, simulate future scenarios, and evoke emotional responses to global challenges [34,36,38]. Nonetheless, most implementations remain disconnected from formal competence frameworks such as GreenComp [2]. Although many studies reference "skills for sustainability" or "transformative learning" [56,57], relatively few explicitly define the sustainability competences they target, limiting the rigor of evaluation. Moreover, AR is often approached as an engaging technological add-on, rather than a pedagogically structured medium intentionally designed to activate or promote specific sustainability competences [35,37].

MARGs represent a particularly promising format for ESD, as they combine multimodal interaction, gamification, and location awareness to foster engagement and knowledge retention [36,41]. Design elements such as narrative progression, task-based challenges, and real-world spatial navigation have been shown to enhance learner agency and promote active participation, aligning, as in the *Art Nouveau Path*, with the competence-oriented vision of GreenComp [2].

To further illustrate this distinction, the *HeritageSite AR* project focused primarily on heritage appreciation and content delivery [41]. By contrast, the *Art Nouveau Path* was conceived from the outset as a GreenComp-aligned educational tool [57].

As presented in Figure 4, the *Art Nouveau Path* integrates four core features: (1) immersive, place-based engagement, (2) alignment with the GreenComp framework [2], (3) activation of sustainability competences (KSA) [2], and (4) integration of intentional pedagogical design.

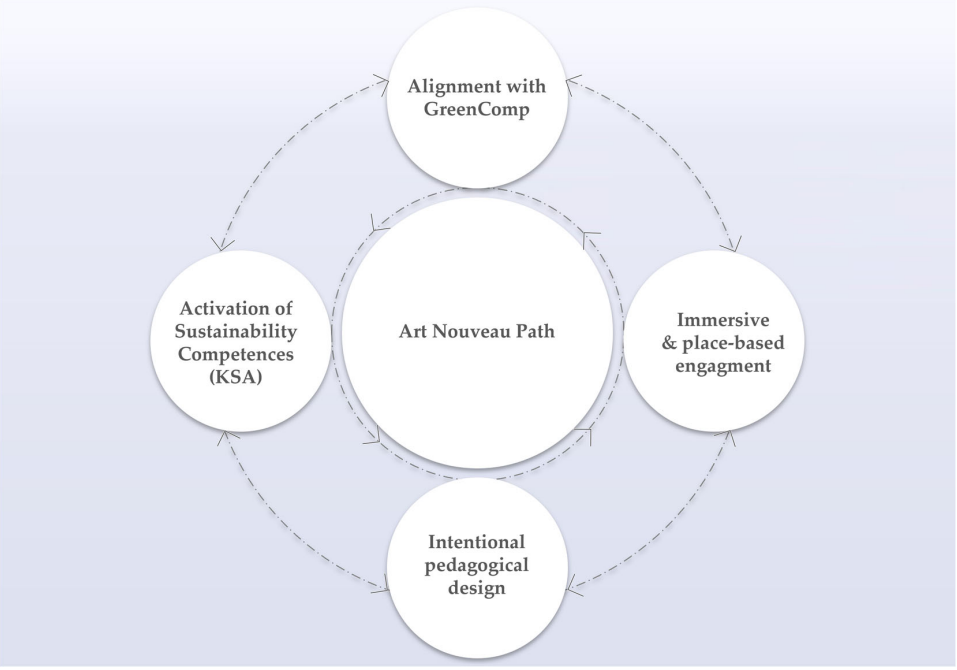

Figure 4. Systemic interdependence in the *Art Nouveau Path*.

Despite AR's growing use in heritage education, many implementations continue to prioritize visual immersion over pedagogical depth. For example, the *EcoMOBILE* project used AR and environmental sensors to support outdoor science education [29],

but it showed limited integration with broader sustainability competences and lacked strong teacher-led or validated design [48]. Similarly, Boboc and colleagues [30] observed that most AR educational applications are technology-driven, with minimal alignment to structured learning frameworks such as GreenComp [2]. By comparison, the *Art Nouveau Path* was specifically designed to address these limitations. Unlike the conventional AR applications, this MARG is anchored in a clearly articulated competence framework, follows a rigorous DBR approach [20,21], and is situated in the lived context of Aveiro's Art Nouveau heritage. In this MARG, AR is not just a technological solution, but rather an indispensable pedagogical medium that engages the emotional, intellectual, and behavioral dimensions of sustainability competence development.

The *Art Nouveau Path* uses geolocated triggers derived from the architectural details of each PI, with 3D and AR overlays, multimodal media, and narrative quiz challenges. These elements are intentionally designed to foster systems thinking, future thinking, and sustainability value awareness. Its narrative, firmly anchored in specific locations, has been shown to enhance emotional engagement and enhance long-term memory retention, which are critical for cultivating sustainability dispositions [39].

Table 1 provides a comparative overview of how the *Art Nouveau Path* differs from other AR-based educational projects. This comparison clarifies the unique contributions of the *Art Nouveau Path*, particularly its integration of competence-oriented pedagogy, GreenComp alignment, and teacher validation, thereby advancing the pedagogical integration of AR in ESD design. This ensures that the comparison highlights not only technical distinctions, but also the pedagogical and competence-oriented contributions of the *Art Nouveau Path*.

Table 1. Comparative overview of three AR-enhanced educational interventions in ESD and heritage-based learning.

Dimension	*EcoMOBILE* [29]	*HeritageSite AR* [41]	*Art Nouveau Path*
Primary Focus	Ecosystem science and water quality analysis	Heritage appreciation through exploration and storytelling	Sustainability competences through built heritage
Target Users	Middle school students	General public, students	Lower and upper secondary education students (research purposes, but publicly available)
Contextual Setting	Natural pond environment	Historical sites in Jakarta	Art Nouveau landmarks in Aveiro, Portugal
Technologies Used	AR app (*FreshAiR*), environmental probeware (*TI NSpire and& Vernier*)	AR mobile app, geolocation, narrative overlays	Mobile AR, multimodal media, EduCITY's platform
Pedagogical Strategy	Situated inquiry, real-time measurement, scientific practice	Spatial exploration, cultural storytelling	Competence-oriented learning (GreenComp), co-designed DBR
Learning Goals	Ecosystem concepts, data literacy, scientific inquiry	Heritage appreciation, cultural understanding	Systems thinking, futures thinking, values awareness
Competence Framework	None (science curriculum alignment only)	None	Explicit integration with GreenComp sustainability competences
Assessment Strategy	Pre-/post-tests, affective and cognitive surveys	Exploratory feedback, no formal evaluation reported	Teacher validation, and GCQuest-based pre-/post-/follow-up questionnaires
Teacher Involvement	Passive: teachers implement fixed materials	Not reported	Validation and curricular review (33 teachers)
Validation Process	Formative feedback + short-term surveys	Not documented	Validation with teachers
Implementation Data	Field-tested with 84 students and 4 teachers	Pilot tested (scope unclear)	Implementation with 419 students and 24 teachers
Replicability and Scalability	Limited (hardware-intensive, teacher-dependent)	Medium (context-dependent)	modular, adaptable to any city via EduCITY's DTLE
Key Strengths	Real-world scientific practice integration	Engagement via narrative and place-based interaction	Holistic competence activation in educational settings

As summarized in Table 1, the *Art Nouveau Path* embeds GreenComp competences into a teacher-validated and competence-oriented design. It contributes to bridge cultural heritage, digital innovation, and ESD within a DTLE framework.

2.4. Designing for Sustainability: Operationalizing GreenComp in the Art Nouveau Path

The GreenComp framework [2] provides a structured and multidimensional reference for embedding sustainability in education. It defines twelve key competences across four interconnected domains: (1) '*Embodying sustainability values*', (2) '*Embracing complexity in sustainability*', (3) '*Envisioning sustainable futures*', and (4) '*Acting for sustainability*'. Together, these domains guide competence-based education toward addressing environmental, social, and economic challenges in an integrated way, and they provide a clear scaffold for aligning learning tasks with targeted outcomes.

Despite growing policy endorsement, many ESD initiatives remain fragmented or declarative [16]. The challenge is not defining sustainability competences, but embedding them in pedagogical practice, curricula, and assessment so that KSA operate as interconnected elements of learning. This requires participatory, reflexive, and context-based approaches that situate learning in the real world. In this study, this gap is aligned by the design of an AR-based learning experience with GreenComp [2] and explicitly mapping each task to the competences it seeks to activate.

While GreenComp has gained traction, few empirical studies offer concrete models for applying it in immersive DTLEs [34,41]. Laherto and colleagues [31] argued that bridging the policy–practice gap requires pedagogical models that operationalize all four GreenComp domains in integrated and meaningful ways. This concern also resonates with prior work that highlights both the transformative potential of competence-based education and the methodological difficulty of assessing transversal competences, such as values, systems thinking, and future literacy [38].

The *Art Nouveau Path* was conceived from the outset to operationalize GreenComp [2] across authentic, place-based activities. Each task in the game is mapped to one or more GreenComp domains, making the targeted learning outcomes explicit. Representative examples draw from our question-level mapping from Question (Q) 1 to Q 36. A summary of representative GreenComp's operationalization is provided in Table 2.

Table 2 maps the *Art Nouveau Path* tasks to GreenComp sub-competences across the four domains. This demonstrates that the game explicitly embeds sustainability competences, extending beyond heritage content to encompass values, systems thinking, future literacy, and collective action. To support orientation and motivation, the MARG's introduction frames the aims and values (1.1; 1.2), and the various PI's directions connect sites through place-based prompts, while the MARG's conclusion emphasizes perseverance and closure (4.2 Motivation and perseverance). A complete, question-by-question map (Q1–Q36) is available at https://doi.org/10.5281/zenodo.16981236.

The pedagogical design is complemented by a formative self-evaluation strategy based on an adapted version of the GCQuest instrument [53]. This tailored tool is aligned with the *Art Nouveau Path* and captures learners' engagement with the 'Embodying Sustainability Values' domain, particularly through the interpretation of artistic and architectural elements. The instrument was administered at three moments, before gameplay, GCQuest-S1PRE diagnostic (available at: https://doi.org/10.5281/zenodo.16540741); immediately afterward, the GCQuest-S2-POST (available at: https://doi.org/10.5281/zenodo.15919739); and again from one to two months later, the GCQuest-S3-FU (available at: https://doi.org/10.5281/zenodo.16540741). This structure supports time-based analysis of how participants self-perceive and reflect on sustainability values. Because the responses were anonymous, a cross-sectional design was adopted. The present paper reports only on the initial diagnostics (S1-PRE).

Table 2. Examples of *Art Nouveau Path* tasks mapped to GreenComp domains and sub-competences.

GreenComp Domain	Example Questions (Q/PI)	Task Description	Linked Sub-Competence
Embodying sustainability values	Q 2 at 'Monument to Liberty'	Reflection on historic water carrying practices, connecting cultural heritage with resource use	1.1 Valuing sustainability
	Q 11 at 'João Mendonça Street'	Environmental impacts of petrol and diesel traffic	1.2 Responsibility for intergenerational justice
	Q 36 at 'Pensão Ferro'	Interpretation of symbolic motifs in stonework	1.1 Valuing sustainability
Embracing complexity	Q 1 at 'Monument to Liberty'	Systems thinking about place, memory, and change	2.1 Systems thinking and complexity
	Q 10 at 'João Mendonça Street'	Quantitative problem with historical measures and materials	2.3 Problem framing
	Q 32 at 'Praça do Peixe' (Fish Market)	Reading inscriptions and temporal context in buildings	2.1 Systems and complexity
Envisioning sustainable futures	Q 5 at 'Monument to Liberty'	Diachronic reasoning about urban change across the 20th century	3.1 Future literacy
	Q 17 at 'Old Agricultural Cooperative'	Speculative thinking about reuse and adaptation (façade tiles)	3.3 Exploratory thinking
	Q 28 at 'Art Nouveau Museum'	AR identification to foster adaptability in new media learning	3.2 Adaptability
Acting for sustainability	Q 12 at 'João Mendonça Street'	Measures against acid rain damage	4.2 Collective action
	Q 23 at 'Aveiro's City Museum'	Advantages of reusing buildings	4.2 Collective action
	Q 34 at 'Praça do Peixe' (Fish Market)	Options for balancing fish consumption and conservation	4.2 Collective action

This design establishes a formative feedback loop in which learning tasks are explicitly mapped to GreenComp domains and revisited through structured self-assessment at three key moments (S1-PRE, S2-POST, and S3-FU). These aims are to promote iterative reflection and consolidate competence development. Figure 5 schematically illustrates how GreenComp informs both the MARG's structure and its assessment strategy, connecting immersive gameplay with reflective practice.

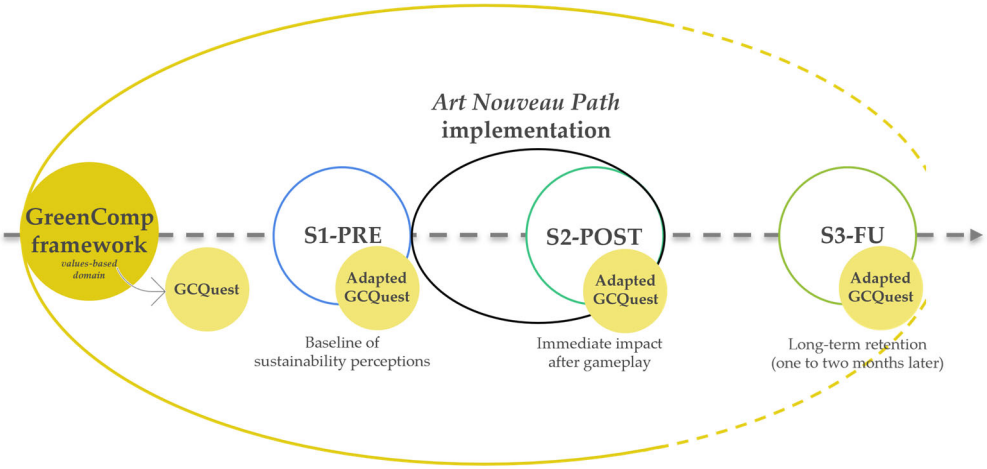

Figure 5. The formative self-assessment cycle linking the GreenComp, the *Art Nouveau Path*, and the adapted GCQuest across three key moments (S1-PRE, S2-POST, and S3-FU).

The present paper focuses on the data derived from two complementary sources: (1) the teacher validation stages (T1-VAL and T1-R); and (2) qualitative responses from the students' pre-test phase (S1-PRE). These datasets provide converging insights into the pedagogical relevance of the *Art Nouveau Path* and are discussed in the Findings section.

The integration of the GCQuest directly relates to the need for assessment strategies that move beyond factual knowledge, focusing on the affective and dispositional dimensions of learning that are often overlooked in formal evaluation [34,57]. By using GreenComp [2] both as a creative scaffold and as an evaluative framework, the *Art Nouveau Path* provides a concrete example of how DTELs can support meaningful and competence-oriented ESD. More than meeting curricular expectations, the MARG encourages learners to engage with sustainability cognitively, ethically, and emotionally through a lens that is both local and future-facing. This emphasis also aligns with the current calls to strengthen psychometric approaches to sustainability competence assessment [38].

This approach is consistent with recent efforts such as the *OpenPass4Climate* project (https://openpass4climate.eu/) (accessed on 17 July 2025), which also operationalizes the GreenComp framework [2] through digital initiatives. This project proposes a system of digital credentials, the 'climate badges', that recognize learners' progress in specific sustainability competences, encouraging active engagement and providing structured feedback on individual action. While *OpenPass4Climate* adopts a distributed, credential-based logic, both these initiatives illustrate how GreenComp [2] can serve as a pedagogical anchor across diverse technological formats, from immersive AR experiences to micro-credential ecosystems.

2.5. Built Heritage as a Learning Platform for Sustainability

Cultural heritage has significant potential for EfS when approached as a context for meaningful, situated learning. From constructivist and sociocultural perspectives, heritage is not merely a repository of the past, but a living medium that fosters identity formation, intergenerational dialogue, and civic responsibility [39,40]. This perspective is reflected in various policy documents such as the '*European Framework Convention on the Value of Cultural Heritage for Society*' [46], which emphasizes cultural heritage as a resource for democratic participation, shared responsibility, and social cohesion. In this sense, heritage is not only an object of preservation, but also a catalyst for community-based action and for engaging learners with contemporary sustainability challenges.

Research on EfS shows that heritage sites can foster critical reflection on human-environment relations, historical continuity, and the ethical implications of conservation, use, and reuse [49,58,59,61]. However, many educational practices remain conceptually fragmented. In schools, heritage is often reduced to content transmission, neglecting its potential to foster competences, such as systems thinking, future literacy, and value-based action [56,57]. More recently, digital technologies have revitalize heritage-based learning. MARGs, in particular, enhanced affective engagement and facilitating embodied, multimodal interactions with historical environments [37,41]. Projects like *HeritageSite AR* [41] and *EduCITY* illustrate how digital tools can integrate architectural narratives, local histories, and urban transformation processes, often strengthened through gamification and storytelling [10,35].

Most existing strategies do not explicitly connect heritage education with established sustainability competence frameworks such as GreenComp [2]. Learners may acquire knowledge about cultural sites or conservation practices, but are rarely encouraged to link this understanding with broader themes of social equity, ecological sustainability, and intergenerational responsibility. Few initiatives offer structured pedagogical models illustrating

how heritage can serve as a framework for developing sustainability competences in a competence-oriented and assessable way.

The *Art Nouveau Path* addresses this gap by treating built heritage not as static content, but as a dynamic learning environment, an active space for exploring sustainability issues through place-responsive pedagogy [46,60]. Each PI operates as a learning node, where architectural and artistic elements are reinterpreted through sustainability lenses. For instance, the Qs at the PI Joaquim Melo Freitas Square (Monument to Liberty, from Q 1 to Q 5) use historical memory and civic symbolism to foster values and systems thinking, while the challenges at the '*Mercado José Estêvão*' (Fish Market) (from Q 32 to Q 34) connect food cultural traditions and biodiversity to collective action. In this way, heritage provides a framework for systems thinking and future literacy, two GreenComp domains often difficult to operationalize in conventional classrooms [32].

As illustrated in Figure 6, the *Art Nouveau Path* acts as a catalyst for sustainability learning by integrating emotional engagement, cognitive challenge, and spatial exploration [33,34].

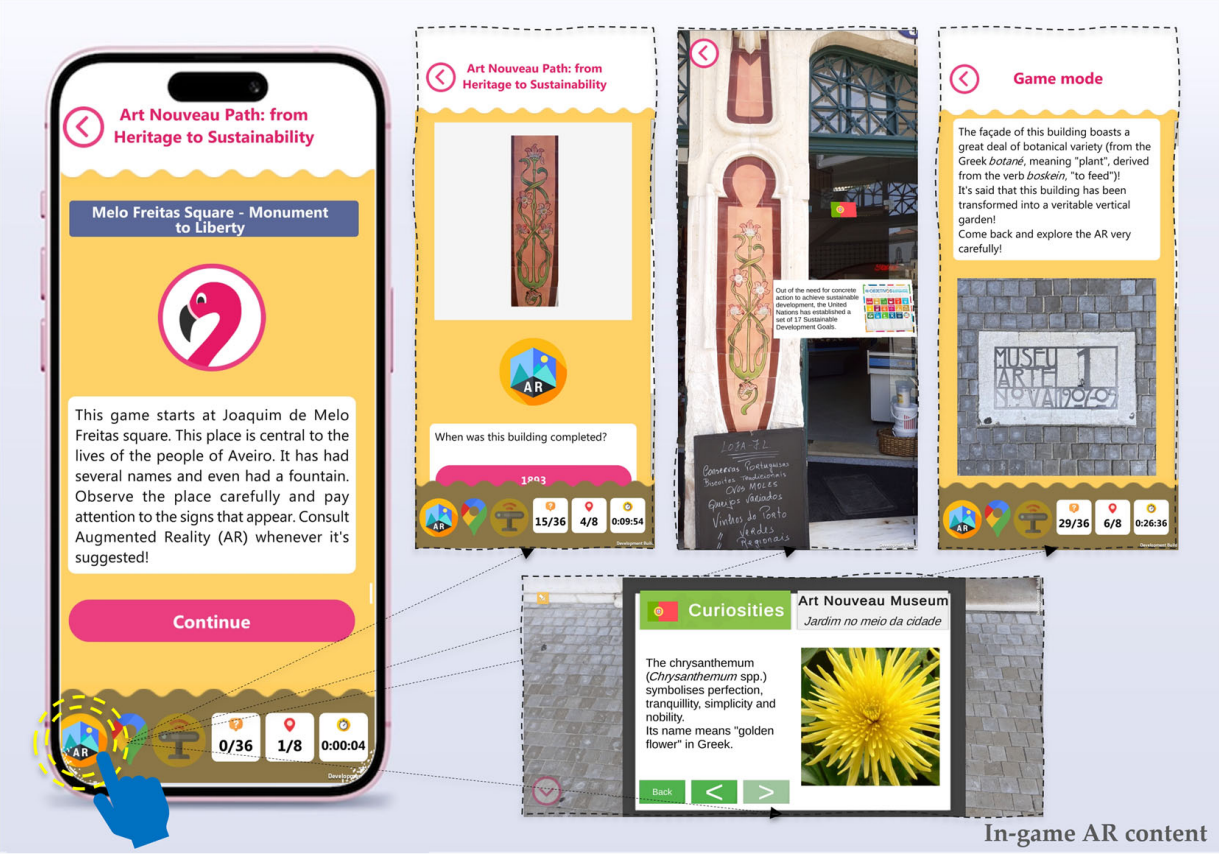

Figure 6. Aveiro's Art Nouveau heritage exploited as AR learning hub to activate GreenComp competences.

The *Art Nouveau Path* advances a model of contextualized citizenship grounded in personal competence and learner agency. As learners navigate the urban landscape and reinterpret its cultural markers through a sustainability lens, they are invited to consider their own roles within broader ecological and societal systems.

For example, the conclusion of the game explicitly emphasizes perseverance and responsibility (Q 36 and the MARG's conclusion), prompting learners to see heritage not as passive inheritance, but as a call to ethical and civic action. This supports a transformative vision of heritage education as a participatory and future-oriented process [31,33,52,56].

3. Materials and Methods

This study adopts an exploratory case study methodology [62,63] within a DBR approach [20,21]. The *Art Nouveau Path* was conceived and implemented as part of the EduCITY DTLE, a research and development initiative hosted by the University of Aveiro (Portugal). EduCITY explores the integration of MARGs into urban and peri-urban educational contexts to foster ESD.

Within the EduCITY context, the *Art Nouveau Path* operates as a place-based and competence-oriented intervention, engaging students with the city's Art Nouveau architectural heritage as both a "living classroom" and an "experiential laboratory" for sustainability competence development. The methodological design combined iterative development, teacher validation, and student implementation, ensuring alignment with the DBR principle of integrating design, enactment, analysis, and redesign [20,21].

It is important to note that while the intervention included three student measurement phases (S1-PRE, S2-POST, and S3-FU), the present paper focuses exclusively on the teacher validation (T1-VAL and T1-R) and on the baseline diagnostics of students (S1-PRE). The analyses of S2-POST and S3-FU will be presented in subsequent publications.

3.1. Study Context and Intervention

The *Art Nouveau Path* MARG was developed between 2023 and 2024 as the research outcome of a doctoral project. Its initial design process combined fieldwork on Aveiro's Art Nouveau built heritage with the creation of digital assets, including 3D models, AR elements triggered by architectural features, and integrated multimedia narratives.

In this MARG, participants progress through 8 PIs in Aveiro's city center, each containing a set of multiple choice, quiz-type questions, narrative prompts, and multimedia resources. Altogether, the game included 36 questions, each following a common structure: an introductory cue, a four-option multiple choice task, and immediate feedback clarifying correctness and providing rationale. Historical photographs, contextualized videos, and audio recordings were embedded as triggers for curiosity, spatial awareness, and critical reflection. The integration of these different contents is presented in Figure 7.

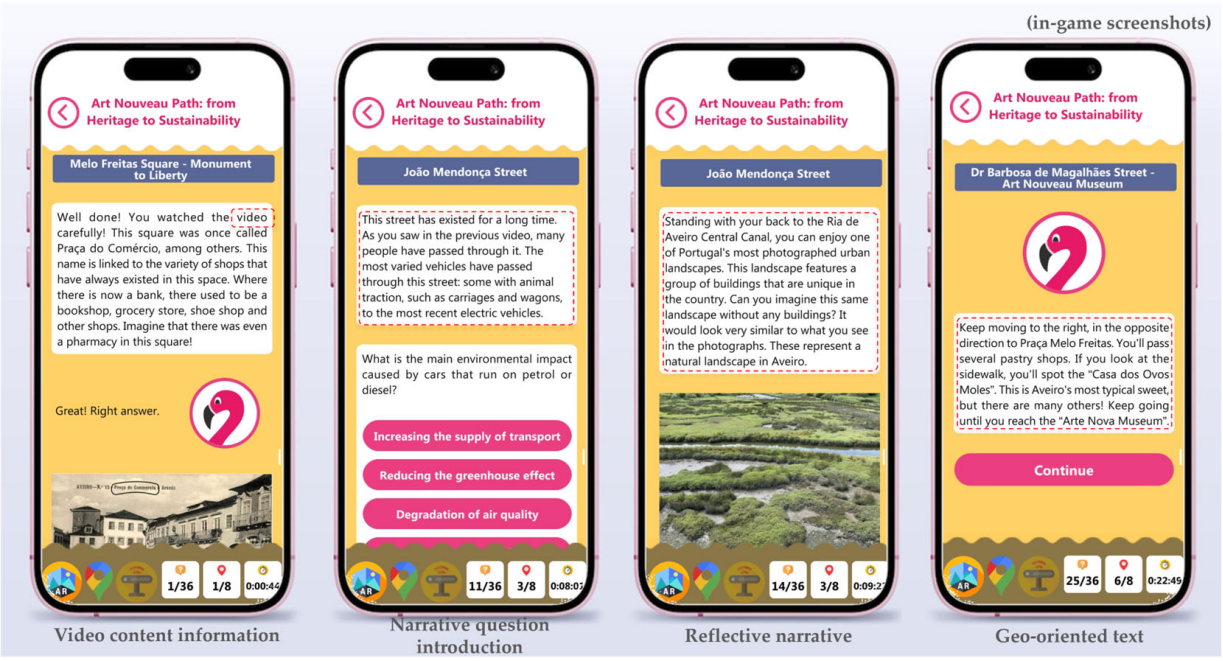

Figure 7. Integration of multimedia and narrative prompts and geolocation tasks in *Art Nouveau Path* MARG.

The quiz challenges were designed to vary in cognitive demand, ranging from 'Remember' to 'Evaluate' levels according to Bloom's revised taxonomy [64]. They intentionally integrate curriculum-relevant content with key themes in sustainability education. Architectural details such as tile panels, ironwork, and floral motifs are used as AR markers, activating "*ARBooks*" or "*Augmented Markers*", containing layered narratives and multimedia experiences, as illustrated in Figure 8.

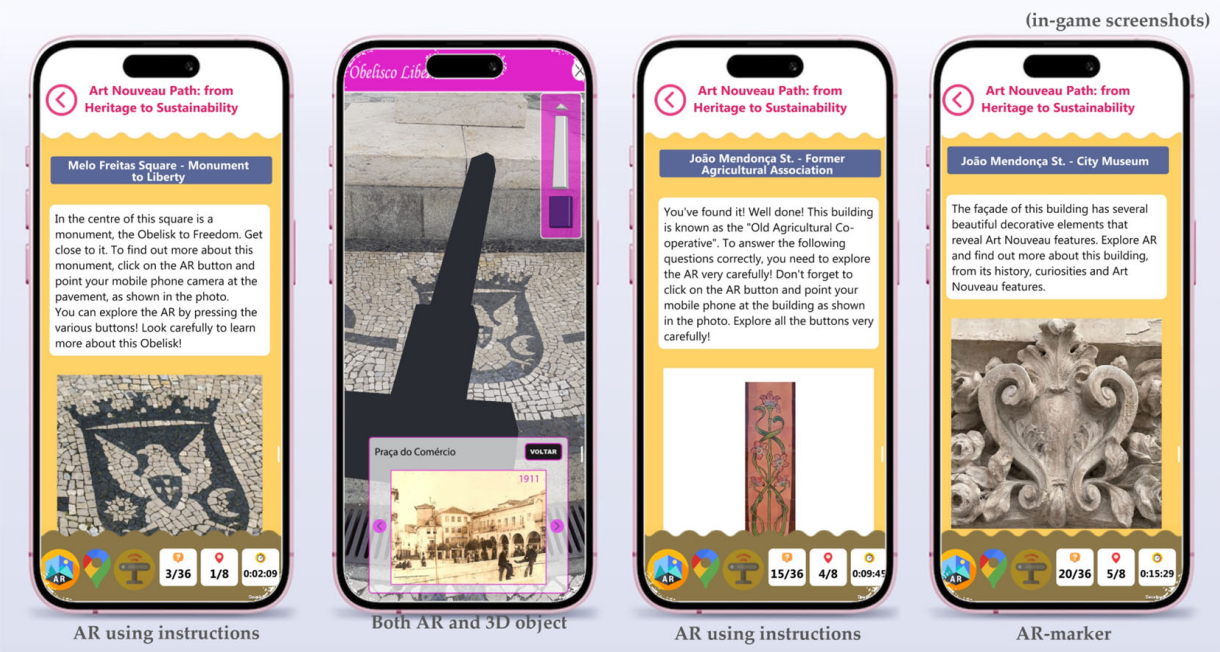

Figure 8. Augmented heritage markers and layered multimedia content in *Art Nouveau Path* MARG.

The narrative at each PI was augmented through the inclusion of historical imagery and original video and audio content, which together nurture a hybrid learning environment, intertwining factual data with interpretative reasoning. For instance, the analysis of decorative details and architectural functions acted as a catalyst for reflection on themes such as resource consumption, environmental stewardship, and sustainability values. The MARG's was designed to be conducive to high levels of learner engagement and situated learning by encouraging real-world exploration and complementing it with digitally mediated heritage narratives. This design aimed to foster a stronger connection between the participants and their urban environment, framing the city not merely as a passive backdrop, but as a dynamic contributor to educational experience [65].

Iterative Refinements

Following the teacher validation phase (T1-VAL and T1-R), several refinements were made to strengthen both the pedagogical and technological dimensions of the MARG. First, one PI ('*Casa do Rossio*', *Rossio's House*) was removed due to content redundancy. Second, the number of quiz questions in '*Pensão Ferro*' was reduced to streamline gameplay. Third, the AR tasks were redistributed and enhanced across three PIs, namely, the 'Old Ala Pharmacy', the 'Aveiro's city museum', and the 'Art Nouveau Museum', integrating additional architectural curiosities and references to local artists. Finally, the two initial PIs were deliberately positioned near provide a gradual introduction to AR mechanics, helping students adapt to the technology while maintaining attention to their physical surroundings.

3.2. Participants and Procedures

This study involved two main participant groups: teachers and students. All procedures complied with the General Data Protection Regulation and the University of Aveiro's ethical guidelines. Participation was entirely voluntary. Informed consent was obtained from the teachers and from the students with additional parental or legal guardians' authorization. No personally identifiable information was collected; therefore, all the datasets are anonymous.

The teacher cohort comprised 30 in-service teachers from the same secondary school in Aveiro, representing different subject areas. All volunteered to participate in the validation workshop (T1-VAL). In addition, three teachers were invited as curricular reviewers (T1-R), selected for their recognized expertise and extensive teaching experience.

Students were recruited through the '*Municipal Educational Action Program of Aveiro*' (PAEMA, 2024–2025 edition), with schools joining voluntarily, resulting in a convenience sample. In total, 439 students participated in the project's implementation, aged from 13 to 18 and studying between the 7th and 12th grades. They were distributed across 19 classes (7th: N = 19; 8th: N = 135; 9th: N = 156; 10th: N = 37; 11th: N = 20; 12th: N = 72), mainly from urban and peri-urban schools. No data on gender or socio-economic background were collected. Regarding the present study, 221 students participated in the pre-test phase (S1-PRE).

3.2.1. Teachers' Validation (Phase T1)

In late 2024, a validation workshop was conducted with 30 in-service teachers (17 female and 13 male) from the central region of Portugal from various curricular areas, such as History, Geography, Arts, Natural Sciences, Mathematics, and Citizenship. Participants were recruited via a teacher-training initiative and engaged in a simulated classroom experience of the *Art Nouveau Path* MARG. Considering the weather conditions, the outdoor activity was replaced with an indoor session using printed AR markers and a prototype version of the EduCITY mobile app (version 1.3). The participants were divided into small groups, replicating the collaborative dynamics experienced by students during gameplay. The mobile devices used were the same EduCITY project smartphones employed in student sessions, ensuring full alignment with the original learning conditions. This arrangement enabled a faithful simulation of the MARG experience in an indoor setting.

Following gameplay, all the teachers completed a mixed-format questionnaire (T1-VAL) composed of Likert-scale items, binary-response questions, and open-ended prompts. The aim of the questionnaire was to assess pedagogical value, usability, and curricular relevance. This instrument (available at: https://doi.org/10.5281/zenodo.15916129) was developed based on validated instruments used in previous studies [66,67].

Concurrently, a curricular review (T1-R) was undertaken by three teachers from different subject areas (History, Natural Sciences, and Arts/Citizenship). Using a structured rubric (available at: https://doi.org/10.5281/zenodo.15917417), their evaluation process focused on its interdisciplinary coherence, its pedagogical robustness, and its contribution to ESD.

3.2.2. Students' Implementations (Phases S1-PRE, S2-POST, and S3-FU)

Student implementation followed three phases: (1) During the baseline diagnostic phase (221 students), they completed the GCQuest-S1PRE diagnostic test (available at: https://doi.org/10.5281/zenodo.16540741). This diagnostic assessed students' initial self-perceived conceptions of sustainability, their interest in cultural heritage, and their readiness for AR-mediated learning; (2) Immediately post-test (S2-POST), 439 students completed the GCQuest-S2POST to capture its short-term impact (not analyzed in this

paper). Additionally, 24 accompanying teachers filled in the T2-OBS observation questionnaire (https://doi.org/10.5281/zenodo.16540603), which assessed student engagement, AR use, and pedagogical relevance under real conditions; (3) During follow-up (S3-FU), from one to two months later, the students completed the GCQuest-S3FU designed to evaluate knowledge retention and sustained engagement with sustainability values.

Across these phases, this study followed a quasi-longitudinal design, relying on anonymous, independent cross-sectional samples. This structure enabled time-based comparisons without requiring individually matched data.

3.3. Data Collection Instruments

Multiple instruments were used to collect the data from both the teachers (Table 3) and the students (Table 3), enabling methodological triangulation consistent with the DBR framework.

Table 3. Overview of teachers' data collection instruments.

Instrument (Code)	Frequency (N)	Focus	Broader Purpose
Teacher's Questionnaire (T1-VAL)	30	Pedagogical value; usability; curricular relevance	Formative feedback for MARG refinement and validation
Teachers Curricular Review(T1-R)	3	Curriculum alignment; interdisciplinary coherence; pedagogical soundness	External curricular validation and content alignment
Teacher Observation(T2-OBS)	24	Student engagement; classroom dynamics; AR use	Triangulation of student experience through teacher observation

The T1-VAL questionnaire elicited both quantitative and qualitative feedback. It was structured around Likert-scale items, binary-response questions, and open prompts (available at https://doi.org/10.5281/zenodo.15916129). The T1-R curricular review addressed six key dimensions: (1) alignment with curricular goals, (2) interdisciplinary articulation across subjects, (3) promotion of critical thinking and reflection, (4) development of observation and analysis skills, (5) application of subject-specific competences, and (6) age appropriateness.

The T2-OBS instrument was used during implementation to register learning dynamics, student engagement, and the integration of AR in authentic settings.

The student data (Table 4) were collected using an adapted version of the GCQuest questionnaire [53], grounded in the GreenComp framework with an emphasis on the '*Embodying Sustainability Values*' domain [2]. The instrument was administered in Portuguese, relying on the official EU translation of GreenComp, which ensured linguistic and conceptual consistency with the framework. Alongside open-ended questions, the instrument presents a scale comprising 25 six-point Likert-scale items. The midpoint was deliberately excluded to encourage more decisive responses [68]. Each administration lasted approximately 20 min. All open-ended questions were contextualized to reflect the themes and experiences of the *Art Nouveau Path* MARG, ensuring content validity and relevance to the educational intervention. Its coding was conducted collaboratively by the authors and another EduCITY project member. This process was based on previous published work [10].

This paper focuses specifically on two components of the study: (1) qualitative findings from the teachers' validation phase (T1-VAL), which complement the previously published T1-R and quantitative results [56]; and (2) baseline diagnostic data collected from the students (S1-PRE).

Table 4. Overview of students' data collection instruments.

Instrument (Code)	Frequency (N)	Focus	Broader Purpose
Student Pre-Questionnaire (GCQuest-S1PRE)	221 [1]	Sustainability values; competence awareness; cultural heritage interest; AR readiness	Diagnostic assessment of students' initial conceptions and expectations
Student Post-Questionnaire (GCQuest-S2POST)	>439 [1]	Perceived learning; engagement with AR; heritage reinterpretation	Evaluation of immediate impact and alignment with game objectives
Student Follow-Up Questionnaire (GCQuest-S3FU)	>439 [1]	Retention of sustainability concepts; reflection on experience	Longitudinal insight into learning retention and attitude development

[1] 439 students engaged in the *Art Nouveau Path* experience, with 221 participating in the pre-test phase (S1PRE), and others completing either post-test (S2POST) or follow-up (S3FU) questionnaires. This study utilizes a quasi-longitudinal structure based on independent cross-sectional samples, allowing for time-based comparisons, while maintaining dataset anonymity and non-pairing, thus not observing strict longitudinal design practice.

3.4. Data Analysis

This study employed a mixed methods analytical framework, combining quantitative and qualitative approaches. The quantitative data from T1-VAL were analyzed through descriptive statistics (means, standard deviations, and frequencies), as reported in another published work [56]. For the student diagnostic (GCQuest-S1PRE), this paper focuses exclusively on yes/no items (Section A), which were summarized using both absolute and relative frequencies. Although Likert-scale items were also collected, their descriptive and psychometric analyses will be addressed in subsequent publications that integrate the complete dataset (S1-PRE, S2-POST, and S3-FU).

The qualitative data were examined using thematic analysis [25,26]. The teacher responses from T1-VAL were coded into themes, such as pedagogical value, engagement, and improvement suggestions. These themes were derived from open-ended responses in Section D of the T1-VAL questionnaire. The T1-R curricular review checked the data crossing with GreenComp [2] and ESD [1,44], verifying curricular alignment. The students' responses to questions such as '*For me, sustainability is*…' were thematically categorized, generating subthemes, such as Environmental Preservation, resource responsibility, and social equity. Coding was performed by the first author and independently reviewed by the second author (supervisor) and a third researcher. Discrepancies were resolved collaboratively until a consensus was reached. No statistical coefficient of inter-coder agreement was computed, but this consensus-based approach ensured analytical trustworthiness. No missing responses were recorded in the quantitative datasets; had they occurred, they would have been handled using available case analyses without imputation. For the qualitative data, occasional non-answers were coded explicitly as a 'No Response/Not Clear'. Additional responses provided insights into respondents' prior knowledge of Art Nouveau heritage and their digital readiness.

Given the exploratory scope, the analyses reported here are limited to yes/no items from the student diagnostic and qualitative findings from teacher validation. Inferential tests (as χ^2, Mann–Whitney U analysis) and psychometric validation of the adapted GCQuest are planned for future work

Triangulating across the teachers and students' datasets enabled a comprehensive evaluation of baseline sustainability conceptions and receptiveness to AR-mediated heritage learning.

Although elements of the teacher validation were reported in previous work [56], this study expands on those findings by offering a comprehensive interpretation of students' initial insights triangulated with teachers' validation (T1-VAL and T1-R). The remaining

datasets (T2-OBS, GCQuest-S2POST, and GCQuest-S3FU) will be analyzed in subsequent publications, thus ensuring analytical depth and avoiding redundancy.

4. Findings: From Teachers' Validation to Students' Diagnosis Insights

This section presents the empirical findings of this study, focusing on two complementary perspectives: (1) teacher validation during the design and pilot phase (T1-VAL and T1-R), and (2) the baseline diagnostic data from the students (S1-PRE). These datasets were selected because they provide converging insights into the pedagogical relevance of the *Art Nouveau Path* and students' initial conceptions of sustainability and heritage.

4.1. Results from T1-VAL

The quantitative results from the T1-VAL questionnaire revealed highly positive evaluations, with mean scores of approximately 5.60/6 for emotional and motivational engagement, 5.43/6 for curricular relevance, and 5.44/6 for overall educational value. The teachers consistently emphasized the MARG's potential to foster systems thinking and place-based learning. The AR features were particularly praised for encouraging new perspectives on urban environments and enhancing observational literacy. These results, which complement the curricular review analysis (T1-R), indicate that the MARG was perceived as both engaging and educationally coherent. More detailed descriptive statistics are reported in a previous publication [56], while the present paper highlights the ways in which these quantitative trends informed the subsequent qualitative analysis and iterative design refinements.

4.1.1. Thematic Analysis of Teacher Feedback

The reflexive thematic analysis [25,26] of the teachers' open-ended responses identified five core themes, summarized in Table 5. These themes provide valuable criteria for evaluating the educational impact of the initiative: (1) Engagement and Motivation, (2) Visual Design and Pedagogical Relevance, (3) Augmented Reality and Technological Integration, (4) Curriculum Integration and Interdisciplinarity, and (5) Sustainability and Reflective Thinking.

Table 5. Emergent themes from teachers' feedback during T1-VAL phase.

Theme	Frequency (N)	Respondents (n)	Description	Example Feedback from Teachers
Engagement and Motivation	31	24	Game elements increase attention, enjoyment, and immersion.	"The game captures students' attention and curiosity" (Teacher (T) 7); "The combination of narrative and AR makes the experience engaging" (T12).
Visual Design and Pedagogical Relevance	21	21	Aesthetic quality and alignment with learning goals are appreciated.	"It is aesthetically attractive and aligned with learning goals" (T18).
AR and Technological Integration	13	13	AR features enhance place-based and interactive learning.	"AR shows new perspectives of the city" (T3); "It encourages students to look at details they normally ignore" (T20).
Curriculum and Interdisciplinarity	9	9	Game connects with multiple school subjects and curricular goals.	"It can be used across different subjects, not only in History or Arts" (T9).
Sustainability and Reflective Thinking	8	8	Stimulates values awareness and sustainability-related reflection.	"The questions make students think about responsible behavior and the consequences of daily actions" (T15).

Considering that open-ended responses contained multiple ideas, units of meaning were often coded into more than one subtheme. Table 5 reports both the frequency of the coded segments (N) and unique respondents (n).

The most prevalent theme was Engagement and Motivation (N = 31), followed by Visual Design and Pedagogical Relevance (N = 21) and Augmented Reality and Technological Integration (N = 13). The teachers described the MARG as "capturing attention and curiosity" (T7) and praised its aesthetic design as "aligned with learning goals" (T18). They valued the AR tasks for prompting closer observation of urban details "that students normally ignore" (T20). References to curriculum integration (N = 9) and sustainability awareness (N = 8) were less frequently given, yet still noteworthy. As one teacher observed, "the questions make students think about responsible behavior and the consequences of daily actions" (T15).

These insights not only validate the MARG's educational potential, but also informed iterative refinements, such as the inclusion of onboarding AR use support and adjustments to the narrative to more clearly integrate sustainability themes.

Overall, the results reinforce the Art *Nouveau Path's* multidisciplinary and motivational value, while also highlighting the need for a clearer and more explicit framing of sustainability in educational initiatives.

4.1.2. Curricular Review Analysis

Three teachers specializing in History, Natural Sciences, and Arts/Citizenship conducted a structured curricular review using a six-dimension rubric: (1) alignment with formal curricular goals; (2) potential for interdisciplinary integration; (3) promotion of critical thinking; (4) development of observation and analytical competences; (5) reinforcement of subject-specific knowledge; and (6) cognitive suitability and age appropriateness. Their disciplinary perspectives provided complementary insights, allowing for a diversified assessment of how the Art Nouveau Path connects with the curricular content and competence-oriented learning objectives.

This review confirmed the strong interdisciplinary alignment of the MARG's content and multiple curricular domains. In History, the game was described as "articulating, in an engaging way, contents from the 9th grade (Portugal in the 20th century) and from the 11th grade (Portugal and Europe—From Liberalism to Estado Novo)" (History teacher). The Monument to Liberty was highlighted as a meaningful entry point for reflecting on republican ideals and civic values. In the Natural Sciences, one reviewer emphasized that "the façades decorated with birds, plants, and shells create an immediate link between artistic expression and ecological knowledge" (Natural Sciences teacher). Another noted that "when students identify limestone façades, they can discuss why this type of rock is more vulnerable to chemical erosion" (Natural Sciences teacher). In Arts and Citizenship, the MARG was praised for "providing concrete opportunities to explore elements of visual language in real contexts, such as line, pattern, rhythm, and texture" (Arts and Citizenship teacher). This teacher also stressed that the game "invites debate about who should protect heritage and how art expresses our relationship with nature" (Arts and Citizenship teacher).

Across all these subjects, the reviewers highlighted the game's capacity to stimulate critical thinking through comparisons between historical and contemporary urban landscapes to foster close visual observation and to cultivate civic responsibility. As summarized by one specialist, the *Art Nouveau Path* "offers students an opportunity to connect history, science, and art with sustainability in ways that are both accessible and challenging" (Arts and Citizenship teacher). The curricular review also confirmed the game's alignment with the GreenComp framework, particularly within the domains of '*Embodying Sustainability Values*' and '*Envisioning Sustainable Futures*' [2]. These findings validate the contribution of

the MARG to competence-oriented ESD practices and reinforce its suitability for interdisciplinary implementation.

4.2. Students' Baseline Analysis (S1-PRE Phase)

Prior to gameplay, 221 students completed the GCQuest-S1PRE diagnostic instrument. This phase was designed to capture the students' baseline self-perceptions of sustainability, cultural heritage awareness, and readiness for mobile AR learning. All the responses were given individually in a supervised setting, following informed consent procedures, which ensured full validity and consistency. This occurred immediately before the sustainability training session with each class. As a self-perception baseline, this diagnostic was limited by the students' low-level prior familiarity, but gameplay mitigated this through the contextualized, competence-oriented tasks.

4.2.1. Sustainability Perceptions and Competence Awareness

The students responded to this open-ended prompt: "For me, sustainability is. . ." (Item A.1.1). The responses were segmented into distinct units of meaning and coded into five subthemes, as presented in Table 6. The most frequent categories included (1) Resource Management and Practices (N = 139); (2) Environmental Preservation (N = 135); (3) intergenerational responsibility (N = 99); (4) Individual Ethical Actions (N = 56); and (6) No Response/Not Clear (N = 18).

Table 6. Students' conceptions of sustainability (A.1.1).

Theme	Frequency (N)	Description	Example Feedback from Students
Resource Management and Practices	139	Recycling, reducing waste, and saving energy.	"Recycle things so they can be used again"; "Save resources so the planet doesn't end"
Environmental Preservation	135	Protecting ecosystems, biodiversity, and nature.	"Take care of animals and plants"
Intergenerational Responsibility	99	Acting sustainably for the benefit of future generations.	"So that in the future people have what we need today"
Individual Ethical Actions	56	Personal responsibility and sustainable behaviors.	"Act correctly every day, even in small things"
No Response/Not Clear	18	Vague or irrelevant responses.	"I don't know what it is"

These findings indicate that students predominantly equate sustainability with ecological behaviors such as recycling and saving resources. By contrast, systemic and abstract dimensions, including responsibility across generations and ethical dispositions, were less frequently articulated. This asymmetry underscores the need for ESD practices that move beyond ecological literacy to foster competences, such as systems thinking and value-based action.

The students also answered three binary-response questions related to sustainability competences (Table 7).

While 73.3% considered them important and 61.1% expressed a desire to learn more, only 51.1% were able to identify any. This reveals both an awareness gap and a pedagogical opportunity: students value the idea of competences, but lack clarity about their scope, reinforcing the need for explicit competence-based framing in sustainability education.

Table 7. Students' awareness and perceived relevance of sustainability competences (from A.2.1 to A.2.3).

Question	Frequency (N)		Percentage (%)		Mean	Standard Deviation
	Yes	No	Yes	No		
A.2.1—Can you name any sustainability competences?	113	108	51.13%	48.87%	0.51	0.50
A.2.2—Do you consider them important?	162	59	73.30%	26.70%	0.73	0.44
A.2.3—Would you like to learn more about them?	135	86	61.08%	38.92%	0.61	0.49

4.2.2. Art Nouveau Knowledge and Heritage Perceptions

In Item A.3.1, the students were asked to describe their understanding of Art Nouveau. Most (N = 123) identified it as a general historical or artistic style. Only 38 referred to its visual characteristics, and just three mentioned Aveiro's local context, despite its recognized Art Nouveau built heritage, as presented in Table 8.

Table 8. Students' knowledge of Art Nouveau and contextual awareness (A.3.1).

Theme	Frequency (N)	Description	Example Feedback from Students
Historical/Stylistic Knowledge	123	General references to style, movement, or period.	"It is an artistic movement with many curved lines and flowers"
No Knowledge/Blank	53	Lack of response or unclear answers.	"I don't know it, maybe it has to do with old buildings"
Recognition of Aesthetic Details	38	Curves, tiles, plant motifs, etc.	"A style with many different shapes and designs on houses"
Connection to Aveiro	3	Explicit reference to local buildings or places.	"The houses in Aveiro with designs on the façades"
Other	4	Miscellaneous or unrelated comments.	"It is an art that decorates houses with tiles and drawings"

These findings confirm that the students' awareness of Art Nouveau was largely generic and disconnected from local heritage. While some identified aesthetic elements, such as curves, tiles, and floral motifs, only three students explicitly mentioned buildings in Aveiro. This limited contextual knowledge substantiates the value of place-based pedagogies that embed heritage into learning experiences using geolocation and visual cues to anchor sustainability competences in meaningful environments.

4.2.3. Attitudes Toward Heritage and Mobile Learning

Items ranging from A.3.2 to A.3.6 explored the students' interest in learning via mobile AR and heritage themes (Table 9). The results were very positive; over 70% expressed interest in learning about sustainability through Art Nouveau, and 80.5% appreciated mobile learning in urban settings, as presented in Table 9.

As presented in Table 9, the data indicates that students have a predominantly favorable attitude towards mobile and heritage-based learning experiences. A significant majority of the respondents expressed an interest in sustainability-related content from an Art Nouveau perspective (72.39%) and a desire to learn more about Art Nouveau buildings in Aveiro specifically (67.87%). This illustrates the educational effectiveness of local heritage as a meaningful framework for ESD. Notably, 79.62% of the students reported finding the MARG theme engaging, and an even higher proportion (80.54%) expressed a preference

for outdoor and mobile learning environments. Together, these findings highlight both the motivational potential of contextualized AR games and the importance of consolidating competence-based frameworks to transform initial interest into sustained learning.

Table 9. Student attitudes toward mobile and heritage-based learning (from A.3.2 to A.3.6).

Statement	Frequency (N)		Percentage (%)		Mean	Standard Deviation
	Yes	No	Yes	No		
A.3.2—Interested in learning about sustainability via Art Nouveau	160	61	72.39%	27.61%	0.72	0.45
A.3.3—Want to learn more about Aveiro's Art Nouveau buildings	150	71	67.87%	32.13%	0.68	0.47
A.3.4—Find the MARG theme interesting	176	45	79.62%	20.38%	0.80	0.40
A.3.5—Like outdoor/mobile learning	178	43	80.54%	19.46%	0.80	0.340
A.3.6—Can distinguish AR from VR	114	107	51.58%	48.42%	0.52	0.50

4.3. Integrated Interpretation and Design Implications

The integration of teacher validation (T1-VAL and T1-R) and baseline student diagnostic (S1-PRE) yielded complementary insights into both the strengths of the *Art Nouveau Path* and opportunities for iterative refinement. The teachers confirmed its pedagogical value and curricular alignment, while the student feedback revealed motivational interest, but also conceptual fragilities, particularly in relation to sustainability competences and knowledge of Art Nouveau. This dual perspective underscored the importance of maintaining curricular adequacy, while strengthening the explicit operationalization of GreenComp [2], within both the MARG and the GCQuest assessment tool [53].

This feedback cycle, characteristic of the DBR approach, enabled iterative refinement, while preserving the MARG's educational integrity. Rather than introducing entirely new directions, the triangulation of perspectives, teachers validating the game's curricular adequacy, and students revealing their baseline misconceptions provided evidence-based guidance for consolidating design choices. Ultimately, the *Art Nouveau Path* is a contextualized and theoretically grounded MARG that supports competence-based ESD through experiential, multimodal learning situated in the built environment.

5. Results: Teachers' Validation and Students' Baseline Insights

This study provides exploratory evidence of the pedagogical relevance of the *Art Nouveau Path* MARG in fostering sustainability competences through culturally grounded and immersive educational experiences. The findings confirm its alignment with the GreenComp framework [2], particularly in domains often underrepresented in practice, such as values, complexity, and futures thinking. While the intervention shows potential as a meaningful component within a DTLE, it should be regarded as a preliminary model whose effectiveness and scalability require further testing in broader and longitudinal contexts [69].

The teachers' validation (T1-VAL) emphasized the MARG's strong educational relevance and capacity to generate emotional engagement. The teachers praised the integration of augmented content, the coherence of design, and the capacity of location-based interaction to capture learners' attention. Importantly, several teachers noted that these features could contribute to competence development only if accompanied by structured pedagogical mediation and teacher preparedness. This observation resonates with GreenComp's emphasis on emotionally engaging and contextualized learning scenarios [2,34,38] with

additional literature on the role of teacher professional development in sustaining digital innovation [18].

The curricular review (T1-R) reinforced these findings, confirming the MARG's alignment with various disciplinary standards in History, the Natural Sciences, Arts, and Citizenship. The reviewers highlighted the game's ability to stimulate critical thinking, visual observation, and interdisciplinary articulation. They also explicitly connected it to the GreenComp domains, such as Embodying Sustainability Values and Envisioning Sustainable Futures. These insights validate the MARG's contribution to competence-oriented ESD, while also reminding us that such alignment does not automatically translate into measurable competence acquisition. Rather, it provides a conceptual foundation that requires further empirical verification across post-test and follow-up phases [32].

The teachers' feedback also identified implementation challenges, particularly regarding digital equity and students' readiness to engage with AR. Such concerns echo systemic barriers frequently reported in DTLEs [27,70]. In response, the design was iteratively refined following the principles of Design-based Research (DBR), for instance by redistributing AR tasks and providing gradual exposure to technology, as presented in Section Iterative Refinements.

This adaptation process ground in DBR [20,21] ensured that the feedback informed both usability and pedagogical alignment. The student baseline diagnostic (S1-PRE) provided an initial snapshot of sustainability awareness and AR readiness. The majority associated sustainability with concrete ecological practices, such as recycling, fewer articulated ethical, systemic, and future-oriented understandings. This confirms that at the baseline, the student conceptions remained predominantly ecological and practical, leaving significant space for competence-oriented scaffolding.

These findings reaffirm the persistent limitations in embedding transversal sustainability competences [2,3,10,69]. They also align with the existing literature that critiques the overemphasis on thematic or content-based knowledge at the expense of integrated competence frameworks [2]. The fact that students recognized sustainability as important, but struggled to articulate competences illustrates this gap clearly, supporting the need for explicit competence-based framing in future implementations [7].

The findings revealed a disconnect between students' emotional investment in sustainability and their cognitive grasp of competence domains. While a notable 73.30% of the respondents considered sustainability competences significant, only 51.1% could name any. This justifies the explicit integration of GreenComp into the MARG's design and assessment strategy. Its architecture, targeting domains such as '*Embodying Sustainability Values*', '*Envisioning Sustainable Futures*', and '*Acting for Sustainability*' [2], was intentionally structured to address this gap.

The students' limited knowledge of Art Nouveau and its connection to Aveiro's heritage further validates the importance of contextual support, scaffolding, and visual cues in the AR content. At the same time, the strong enthusiasm expressed for heritage and mobile-based learning demonstrates the motivational potential of combining cultural heritage with digital tools. This dual finding (low-level prior knowledge, but high-level interest) reinforces the value of place-based learning designs that anchor competence development in familiar, yet underexplored environments [12,13].

Approximately 70% of the students expressed interest in exploring sustainable practices through the lens of Art Nouveau, and 80.54% valued mobile learning formats. However, only 51.58% could distinguish between AR and VR, pointing to the need for additional support in cultivating foundational digital literacies [42,71,72]. This highlights an important precondition for successful implementation: without strengthening students' basic digital

competences, the pedagogical affordances of immersive technologies risk being unevenly realized [45].

Taken together, these integrated findings support the assertion that embedding cultural heritage meaningfully within DTLEs, when underpinned by competence frameworks such as GreenComp [2], can enhance ESD. The *Art Nouveau Path* illustrates how emotional investment, reflective questioning, and localized experiences may foster systemic reasoning and ethics-oriented learning. Its design nurtures personal connections to urban environments and cultural identities, resonating with the principles of affective and holistic pedagogical approaches [73,74]. Although, the exploratory nature of this study supposes that such claims should be treated as indicative rather than conclusive.

Moreover, the iterative co-evaluation process, combining teacher validation and student diagnosis, generated actionable insights that guided pedagogical enhancement. This feedback-oriented strategy exemplifies the participatory and adaptive design ethos of DBR, ensuring that technology-enhanced methodologies were not imposed, but rather co-shaped with stakeholders. Such an approach strengthens both ecological validity and the likelihood of sustainable adoption in formal education [18,20].

More broadly, the *Art Nouveau Path* offers an exploratory model for incorporating ESD into real-world and cultural contexts, while maintaining curriculum alignment and technological accessibility. Its narrative logic draws on the aesthetic coherence of Art Nouveau as '*Gesamtkunstwerk*' ('total work of art') to promote cognitive and emotional cohesion. At the same time, its successful transfer to other contexts depends on structural conditions, such as teacher training, equitable access to digital resources, and integration into local curricular priorities. These practical considerations temper claims of replicability, while still highlighting the model's value as a source of inspiration for culturally rooted approaches to ESD [15,16,46]. By translating theoretical competence frameworks into immersive, emotionally resonant learning experiences, the Art Nouveau Path responds to current calls in ESD frameworks for integrative methodologies that promote agency and value internalization, as well as future-oriented thinking [2,25].

As this study demonstrates, carefully designed MARGs can make a meaningful contribution to advancing the role of DTLEs in sustainability education. Nevertheless, this contribution should be regarded as preliminary, with its long-term effectiveness contingent on further empirical evidence. Future research will extend this work through cross-sectional analyses of the S1-PRE, S2-POST, and S3-FU datasets, enabling a more nuanced understanding of how sustainability competences evolve across different phases of the intervention.

6. Final Reflections, Limitations, and Future Path

This study reports the design, implementation, and the preliminary findings from the evaluation of the *Art Nouveau Path*, a MARG developed within the EduCITY DTLE. By connecting the GreenComp-aligned activities to local built heritage, the intervention seeks to activate sustainability values, systems thinking, and future literacy in authentic urban environments. It is important to note that this paper presents a subset of a broader research program, focusing specifically on teacher validation and baseline student data. The subsequent post-test (S2-POST), follow-up (S3-FU), and observation datasets will be analyzed in separate publications to ensure analytical depth and avoid redundancy.

Teacher validation (T1-VAL and T1-R) provided positive feedback regarding motivational appeal, interdisciplinary value, and curricular alignment. The teachers highlighted the relevance of connecting sustainability education with local cultural heritage when mediated through immersive technologies. The game was considered compatible with the curriculum goals, and aligned with the key GreenComp domains, particularly '*Embodying sustainability values*' and '*Envisioning sustainable futures*' [2].

The baseline analysis (S1-PRE) provided insights into the students' initial readiness for sustainability- and heritage-focused learning. The binary-response items indicated strong interest in mobile AR and outdoor experiences, whereas the open-ended responses revealed limited familiarity with sustainability competences and with Aveiro's Art Nouveau heritage. Although many students expressed value-driven attitudes and curiosity, only a minority articulated specific competences or identified stylistic architectural elements. This finding underscores the diagnostic function of the baseline, highlighting the need for explicit scaffolding to make competence domains visible to learners from the outset.

Aligned with the GreenComp framework [2], the *Art Nouveau Path* prioritizes the '*Embodying Sustainability Values*' domain, while establishing foundations for transversal engagement with systems thinking, future literacy, and collaborative action. Integrating AR into real-world environments contributes to expanding research on how digital tools situated within local cultural heritage can support ESD in engaging, inclusive and contextually relevant ways. Importantly, the GCQuest instrument used in this study has already undergone psychometric validation in a previous publication [10]. A second-order SEM model (N = 358) demonstrated a good fit (CFI = 0.945, TLI = 0.939, SRMR = 0.049, RMSEA = 0.077; all loadings $p < 0.001$), providing robust evidence for the instrument's factorial structure and construct validity. In the present article, however, we report only the baseline diagnostic results.

Beyond the practical insights, this research contributes theoretical and methodological perspectives on how to design and assess DTLEs that combine technological innovation with educational authenticity. The DBR approach, informed by teacher validation and baseline diagnostics, enabled iterative refinements, such as redistributing AR tasks, adjusting onboarding, and clarifying competence prompts. This exemplifies how teacher and student input can guide redesign, ensuring alignment with GreenComp, while maintaining adaptability to diverse educational contexts.

This study presents several limitations. First, it adopts an exploratory case study design and reports only a subset of the wider research program, namely teacher validation and baseline student data (S1-PRE). Second, it is important to acknowledge, however, that this diagnostic captures self-perceptions rather than tested knowledge, and many students entered the activity with limited familiarity with sustainability competences or Art Nouveau heritage. This limitation is intrinsic to the baseline designs, but was mitigated by situating the subsequent gameplay within contextualized, competence-oriented tasks. Third, because the responses were collected anonymously and organized as cross-sectional cohorts, it was not possible to conduct matched pre–post comparisons at the individual level. Fourth, the analyses presented are primarily descriptive, with inferential and longitudinal tests reserved for future publications. Fifth, although the Portuguese adaptation of the GCQuest has been psychometrically validated in a separate study [10], further testing is required across different age groups and educational contexts to consolidate its robustness. Exploratory ω values were also computed using JASP 0.19.3 across the three measurement points: S1-PRE = 0.724, S2-POST = 0.866, and S3-FU = 0.768. Although the GCQuest was designed as a multidimensional instrument, reporting a global ω provides an exploratory indication of whether all the items together form a coherent overall measure, supporting the use of a total score and enabling longitudinal comparisons. Sixth, although the gender data were not collected, which limits the demographic characterization of the sample, previous studies in sustainability education and competence development [75,76] suggest that gender is not a critical determinant of outcomes in this type of intervention. Therefore, its omission does not compromise the validity of the present analysis. Seventh, no statistical index of inter-coder agreement (e.g., κ) was calculated for the qualitative coding; instead, reliability was ensured through collaborative consensus among three researchers.

Taken together, these limitations reinforce the exploratory and formative scope of the present article, which will be complemented with subsequent publications with post-test and follow-up datasets.

Future research will integrate S2-POST and S3-FU to examine the learning outcomes, emotional engagement, and the development of sustainability competences over time. The planned analyses include inferential tests, subgroup comparisons, and expanded reliability reporting at both the subscale and global levels. Building on previous SEM validations already published elsewhere, the forthcoming analyses will complement these results with Cronbach's α for individual factors, McDonald's ω for hierarchical reliability, and additional SEM-based indices (like composite reliability, AVE, and HTMT) to more accurately capture the multidimensional structure of the GCQuest. Comparative studies will also contrast AR-based learning with analogue alternatives (e.g., board or card games) to clarify the added pedagogical value of augmented spatiality. Adaptations for different age groups and inclusive co-design with students and teachers are planned to enhance ownership and contextual relevance.

Exploring the scalability and cultural adaptability of the *Art Nouveau Path* represents a valuable path for future research. However, any transfer to other urban or heritage contexts will depend on enabling conditions, such as infrastructure, connectivity, teacher professional development, and local policy priorities. Future design improvements will emphasize inclusive co-design, actively engaging students and teachers as partners to strengthen ownership, contextual relevance, and educational impact.

The *Art Nouveau Path* illustrates how MARGs grounded in cultural heritage can foster sustainability competences and enrich digital teaching and learning ecosystems, provided that competence mapping, assessment strategies, and iterative refinement are clearly embedded in the design.

In the context of the growing emphasis on experiential, value-oriented, and technologically mediated education, the Art Nouveau Path provides an exploratory model that connects learners with their environments and communities. Its scalability and transferability remain conditional on infrastructural, pedagogical, and policy factors, including teacher professional development and equitable access to technology. Within these conditions, the approach can help students envision and enact their future roles as agents of sustainable transformation.

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Data Availability Statement: Summarized datasets are deposited in the Zenodo repository, including: teachers' T1-VAL and T1-R data (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-R Questions: https://doi.org/10.5281/zenodo.15917417; and T1-R—Analysis Data: https://doi.org/10.5281/zenodo.15917517). Datasets regarding students' S1-PRE, S2-POST, S3-FU, and T2-OBS are still under analysis, and after deposition will be available from the corresponding authors upon reasonable request.

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Abbreviations

The following abbreviations are used in this manuscript:

ESD	Education for Sustainable Development
UNESCO	United Nations Educational, Scientific and Cultural Organization
SDG	Sustainable Development Goal
EfS	Education for Sustainability
MARG	Mobile Augmented Reality Game
DTLE	Digital Teaching and Learning Ecosystem
PI	Point of Interest
AR	Augmented Reality
DBR	Design-based Research
RQ	Research Question
KSA	Knowledge, Skills and Attitudes
Q	Question

Appendix A

Table A1. Selected peer-reviewed articles.

Reference	Methodological Approach	Main Focus	ESD Domains/GreenComp	Subsection
[27]	Literature review	Learning spaces supporting sustainability	Systems thinking; Acting for sustainability	2.2
[28]	Empirical study (quasi-experimental)	AR for physical sustainable education	Motivation; Learning to act	2.3
[29]	Field experiment (AR + probeware)	Outdoor environmental education	Systems thinking; Critical thinking	2.3
[30]	Bibliometric review	AR in cultural heritage (trends)	Cross-domain	2.3
[31]	Theoretical/conceptual (GreenComp focus)	Future-oriented science education	Futures literacyFuture literacy; Systems thinking	2.1
[32]	Conceptual (dialogue format)	Heritage futures and& sustainability	Futures literacyFuture literacy; Valuing sustainability	2.5
[33]	Analytical/applied	Digital transformation in heritage education	Innovation; Responsibility	2.5

Table A1. *Cont.*

Reference	Methodological Approach	Main Focus	ESD Domains/GreenComp	Subsection
[34]	Conceptual paper	ESD as catalyst for local SDG transitions	Systems thinking; Responsibility	2.1
[35]	Evaluative study (heritage programs)	AR/VR in heritage education	Valuing sustainability; Systems thinking	2.3
[36]	Empirical (elementary schools)	AR in cultural education	Valuing sustainability; Pedagogical competence	2.3
[37]	Conceptual/analytical	Emerging digital technologies in education	Futures literacyFuture literacy; Digital competence	2.2
[38]	Longitudinal study	ESD effectiveness on action competence	Acting for sustainability; Responsibility	2.1
[39]	Quantitative (survey)	Psychosocial predispositions and& environmental identity	Sustainability values; Responsibility	2.1
[40]	State-of-the-art review	AR in education: teaching and learning revolution	Future literacy; Digital competence	2.3
[41]	Mixed methods	HeritageSite AR exploration game for SDGs	Valuing sustainability; Future literacy	2.3
[42]	Handbook chapter (review)	AR teaching and learning affordances	Cross-domain (motivation, engagement)	2.3
[43]	Meta-review and cross-media analysis	AR in education effectiveness	Critical thinking; Systems thinking	2.3

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