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INFORMATION AND ANALYTICAL SYSTEMS IN ARCHAEOLOGY AS TOOLS FOR BUILDING A DIGITAL CULTURAL HERITAGE ECOSYSTEM AND IMMERSIVE EXPERIENCES

Abstract. *The article examines information and analytical systems in archaeology as tools for the digitalisation of cultural heritage aimed at forming immersive experience. It is substantiated that contemporary digital archaeology should move from creating separate 3D copies of artefacts, monuments, or archaeological landscapes towards building semantically enriched digital twins suitable for analysis, planning, learning, popularisation, and remote interaction. Within this approach, the digital recording of an object using photogrammetry, laser scanning, LiDAR, photo and video data, GIS referencing, and sensor data is considered as the initial stage in the formation of a digital environment. Gaussian Splatting is defined as a promising tool for the photorealistic 3D representation of an archaeological object, which can be supplemented with analytical layers of recognition, segmentation, measurement, damage detection, spatial navigation, and semantic description.*

The article proposes an operational model of a semantically enriched digital twin of archaeological heritage, combining 3D recording, Gaussian Splatting, AI support, knowledge bases, digital storytelling, gamification, elements of Serious Games, continuous learning, and cultural tourism scenarios. Such a digital twin can be used not only for the visual representation of a monument, but also for preliminary familiarisation of the research team with the object, fieldwork planning, identification of areas of interest, task distribution, preparation of survey routes, and reduction of unprepared physical interventions. Particular attention is paid to the possibility of using digital twins in the training of archaeology students, museum professionals, specialists in digital heritage, multimedia technologies, and tourism, as well as in the creation of virtual routes, learning tasks, popular science scenarios, and forms of remote access to archaeological objects.

Keywords: *information and analytical systems, digital archaeology, cultural heritage, digital twin, Gaussian Splatting, 3D recording, semantic enrichment, artificial intelligence, immersive experience, gamification, Serious Games, continuous learning, cultural tourism.*

INTRODUCTION

Contemporary archaeology is increasingly developing toward digitalization, which includes not only the recording of artifacts, monuments, and archaeological landscapes, but also the further processing, analysis, interpretation, and presentation of the collected data in a digital environment. Archaeological cultural heritage is a complex object of study because it combines material, spatial, historical, cultural, educational, and communicative characteristics. For this reason, its digital representation cannot be limited to the creation of a visual copy of an object. It becomes important to create a digital environment in which an archaeological object can not only be viewed, but also described, analyzed, linked to sources, enriched with semantic data, and used in various scenarios of scholarly, educational, museum, and tourist interaction.

In this context, information and analytical systems acquire particular importance, since they are able to integrate different stages of work with archaeological heritage: digital recording, 3D representation, analytical enrichment, metadata management, AI support, visualization, immersive interaction, and further data updating. This approach makes it possible to view the digitalization of archaeology not as a set of separate tools, but as an integrated process of transforming an archaeological object into a semantically enriched digital twin. Such a digital twin can serve as an intermediary between the physical monument, the research team, the educational environment, museum practice, tourist communication, and the wider public.

One important direction of this development is the use of modern technologies for 3D recording and photorealistic representation of objects. Photogrammetry, laser scanning, LiDAR, GIS referencing, and photo and video documentation create the basis for the further formation of a digital model of an archaeological object. In this context, Gaussian Splatting should be considered not as a replacement for all other methods, but as a promising method of photorealistic 3D scene representation suitable for immersive navigation and visual

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immersion. At the same time, its potential for archaeology becomes more fully realized when the photorealistic model is supplemented with analytical and semantic layers: object recognition, segmentation, measurements, damage detection, description of areas of interest, and links to typologies, sources, and knowledge bases.

The practical relevance of this approach is connected with the specific nature of work with archaeological objects. Many monuments are fragile, partially destroyed, difficult to access, or require restrictions on physical intervention. The creation of a semantically enriched digital twin makes it possible to familiarize the research team with the object in advance, identify areas of interest, prepare survey routes, distribute tasks among team members, develop a fieldwork plan, and reduce the number of unprepared actions directly at the site. After a new field stage, the digital twin can be updated with observation results, photographic records, refined hypotheses, and new semantic annotations.

Educational, tourist, and popular science scenarios for using such systems are also of particular importance. A semantically enriched digital twin can be used to train archaeology students, museum professionals, specialists in digital heritage, multimedia technologies, tourism, and interdisciplinary teams within the framework of continuous learning. In this environment, the user can not only view the object, but also complete learning tasks, follow virtual routes, become familiar with the archaeological context, receive explanations, and interact with the object in an immersive mode. In this approach, gamification and elements of Serious Games are not treated as entertainment add-ons, but as possible mechanisms for engagement, learning, and the popularization of cultural heritage.

Therefore, the relevance of this study is determined by the need to move from separate digital models of archaeological objects to information and analytical systems that provide analytical, semantic, educational, immersive, and communicative functionality. In this article, archaeological heritage is considered not only as an object of digital preservation, but also as a basis for creating an operational digital environment capable of supporting research, learning, planning, cultural tourism, and responsible interaction with monuments.

PROBLEM STATEMENT

Despite the active development of digital methods in archaeology, a number of methodological and technological gaps remain in the practice of working with archaeological cultural heritage. On the one hand, researchers are increasingly using photogrammetry, laser scanning, LiDAR, GIS, 3D modeling, digital databases, artificial intelligence tools, and immersive technologies. On the other hand, these tools are often applied in a fragmented way: the 3D model exists separately from field documentation, metadata separately from visualization, analytical results separately from educational and museum scenarios, and tourist or popular science communication separately from research logic.

As a result, a significant share of digital archaeological models remains primarily visual objects. They may be useful for demonstrating the form of an artifact, the spatial structure of a monument, or a reconstruction of an environment, but they do not always support analytical work with data. The problem is that photorealism or geometric accuracy alone does not ensure the full digitalization of archaeological heritage. For a researcher, it is important not only to see an object, but also to be able to identify its elements, measure them, and link them to descriptions, sources, dating, typologies, previous observations, hypotheses, and the results of further fieldwork.

This issue is especially relevant for Gaussian Splatting technologies. Their development opens new possibilities for creating photorealistic immersive representations of archaeological objects and spaces. However, without additional analytical and semantic enrichment, such models may remain only an impressive visualization method. For archaeological practice, it is important to move toward an understanding of Gaussian Splatting as one component of a broader information and analytical system in which photorealistic representation is combined with object recognition, segmentation, spatial analysis, semantic annotations, knowledge bases, and immersive interaction scenarios.

Another problematic aspect is related to the use of digital models in fieldwork planning. An archaeological object often requires careful, gradual, and well-prepared interaction. Unprepared or excessive physical interventions may lead to additional pressure on the monument, increased time and resource costs, duplication of actions by different team members, and the loss of part of the contextual information. A semantically enriched digital twin can partly address this problem because it allows the team to work with the object in advance in a digital environment: to identify areas of interest, create routes, distribute tasks, prepare checklists, and refine the program of further survey work.

The integration of scholarly, educational, tourist, and public uses of digital archaeological models also requires particular attention. University programs, museum activities, cultural tourism, and popular science communication often require different formats for presenting the same object. For a researcher, sources, accuracy, evidence, and the possibility of repeated verification are important. For a student, clear navigation, learning tasks, and the possibility of gradual immersion in the material are essential. For a tourist or general audience, accessibility, visual persuasiveness, storytelling, and motivation for interaction are important. The absence of a unified information and analytical model makes it more difficult to reuse digital data across these different scenarios.

Thus, the scholarly problem lies in the lack of a coherent operational model that would make it possible to transform the digital recording of an archaeological object into a semantically enriched digital twin suitable not only for visualization, but also for analysis, planning, learning, immersive interaction, gamification, Serious Games, and cultural tourism. The applied problem lies in the need to create an approach that will reduce the fragmentation of digital archaeological data, improve the effectiveness of fieldwork preparation, ensure the reuse of 3D models and metadata, and expand access to archaeological heritage for students, specialists, museum professionals, tourists, and the wider public.

The scientific novelty of the article lies in the substantiation of an operational model of a semantically enriched digital twin of archaeological heritage, in which 3D recording, Gaussian Splatting, analytical recognition, semantic enrichment, AI support, immersive interaction, gamification, Serious Games, and tourist and communication scenarios are considered as interconnected components of a single information and analytical system. This approach makes it possible to shift the focus from creating a separate digital copy of a monument to forming a digital environment that supports the full cycle of work with an archaeological object: from recording and analysis to planning, learning, popularization, and further data updating.

REVIEW OF CURRENT RESEARCH AND PUBLICATIONS

In recent years, digital archaeology has significantly changed its instrumental and methodological horizon. Whereas digital technologies were previously often perceived as auxiliary tools for recording or visualizing archaeological material, today they increasingly shape the full cycle of work with an object: from field recording and spatial scanning to semantic description, machine processing, immersive representation, and data reuse in scholarly, educational, and tourist scenarios. This logic is visible in contemporary studies of 3D documentation, artificial intelligence, Linked Open Data, digital twins, archaeogaming, and Serious Games.

The initial level of such digitalization remains high-quality recording of an archaeological object. The CAA 2026 materials emphasize the importance of integrated 3D documentation that combines terrestrial laser scanning, airborne and unmanned aerial laser scanning, bathymetric laser scanning, photogrammetry, GIS integration, and the preparation of data for further spatiotemporal analysis [1]. Thus, digital recording in archaeology is no longer simply the creation of an image or model. It becomes a process of forming a multi-aspect dataset suitable for further analytical, interpretive, and communicative work.

In this context, Gaussian Splatting deserves a separate place, but not as an isolated “fashionable” technology. Rather, it should be considered a new method for the photorealistic representation of archaeological space. Kerbl et al. [2] proposed the technical basis of 3D Gaussian Splatting for real-time radiance field rendering, which opened up the possibility of creating high-quality scenes suitable for interactive viewing in real time. In the field of cultural heritage, this logic is developed in [3], where Gaussian Splatting is considered as a tool for immersive heritage and reality capture. For our study, it is important that this technology makes it possible not only to show an archaeological object, but also to create a basis for further navigation, immersion, and interaction with space.

At the same time, photorealism itself does not guarantee the scientific value of a digital model. An archaeological object requires not only visual reproduction, but also structured description, possibilities for measurement and segmentation, recording of condition, connection with context, and verification of interpretations. Therefore, the promising direction is not simply the use of Gaussian Splatting to create an impressive image, but its inclusion in a broader information and analytical system. In such a system, the photorealistic scene should be supplemented by an analytical layer: object recognition, identification of areas of interest, spatial measurements, recording of damage, semantic annotations, and links to knowledge bases.

The idea of a digital twin makes it possible to move from a model as a visual copy to a model as an operational environment. In [4], cultural heritage digital twins are connected with sensor data and ontological description, which makes it possible to form not a static image, but a structured environment for observation and interpretation. In [5], the digital twin is combined with IoT and predictive maintenance, that is, with monitoring the condition of an object and supporting decisions on its preservation. For archaeology, this is especially important because many monuments are vulnerable, partially destroyed, or restricted for regular physical access.

The next step after creating a digital model is its semantic enrichment. In the CAA 2026 materials, the Kompakkt platform is presented as a tool for publishing, documenting, annotating, and semantically enriching 3D cultural heritage objects [6]. Its connection with IIIF 3D, Wikibase, FAIR principles, persistent identifiers, and machine-readable documentation shows that a 3D object can be not only a multimedia resource, but also part of a scholarly knowledge infrastructure. Practices of Linked Open Data in archaeology, including the implementation of archaeological data in Wikidata, are developing in the same direction [7].

The quality of such a semantic layer directly depends on the quality of metadata. In [8], the problem of metadata completeness in digital cultural heritage repositories is examined. For the model proposed in this article, this is of fundamental importance: a digital twin of an archaeological object cannot be complete if it consists only of a 3D scene. It must contain, or support links to, descriptions, sources, dating, typologies, contexts, hypotheses, and the history of changes.

It is also important to note approaches in which artificial intelligence is used not to automatically replace expert interpretation, but to support the structured analysis of archaeological information. In [9], the cultural significance of archaeological sites is considered through spatial networks of meanings. In the CAA 2026 materials, the InSites approach is presented as a Human–AI workflow in which GenAI acts as a reflective partner for working with fragmented evidence, missing information, significance statements, knowledge graphs, and interactive views [10]. It is important that this approach is directly connected with the principles of methodological alignment, cognitive transparency, and strict evidence grounding. This corresponds well to the need to prevent AI-generated narratives from becoming detached from the archaeological context.

The recommendations of the European Archaeological Council on assessing archaeological significance [11] also provide an important framework for the responsible use of digital technologies. They remind us that work with archaeological heritage is always connected with evidence, context, the value of the object, the limits of interpretation, and ethical decisions. Therefore, AI, gamification, VR/AR, or tourist scenarios cannot be treated as neutral decorative additions. They must be based on verified data and expert logic.

Contemporary reviews of AI and machine learning in archaeology show that these tools are already used quite widely. In [12], the possibilities and risks of managing AI in archaeology are systematized. The review by Bellat et al. [13] demonstrates the application of machine learning to object classification, structure recognition, image analysis, and predictive modeling. In [14], artificial intelligence is considered in the context of archaeological site conservation. Within this article, these sources are important for substantiating the AI layer of the digital twin: it can support analysis, search, preliminary classification, and change detection, but it should not replace archaeological judgment.

The use of 3D models in the academic environment is gradually moving beyond purely technical documentation. In [15], the use of finite element methods and laser scanning documentation is analyzed, showing the connection between digital recording, diagnostics, and object modeling. In [16], attention is paid to the creation and use of 3D models in universities. This makes it possible to view 3D models not only as a result of research work, but also as a resource for object-based learning, demonstrations, learning tasks, and interdisciplinary training.

The educational dimension of digital archaeology is especially visible in projects where a 3D model is combined with a narrative. The CAA 2026 materials present a workflow for creating a 3D edition of an archaeological object for teaching students of archaeology and cultural heritage [17]. This example is important for our logic because it shows that a 3D model can be not merely an object for viewing, but also an environment for explanation, engagement, assessment of perception, and gradual immersion in context.

Another direction is connected with gamification, archaeogaming, and Serious Games. In the CAA 2026 session “Beyond Fun and Games?”, games, game engines, VR installations, and museum interactives are considered as tools for communication, critical reflection, engagement, and learning [18]. A concrete example of a serious VR game for prehistoric heritage is presented in [19], where interaction with a digital environment is used for public engagement with prehistoric heritage. These approaches make it possible to move from passive viewing of an object to active performance of actions in digital space.

The theoretical foundations of Serious Games in the field of cultural heritage are discussed in [20], where their educational and dissemination potential for archaeological heritage is emphasized. The study [21] examines location-based games and underlines the importance of spatial reference, route, local context, and interaction design. In [22], an assessment instrument for games related to cultural heritage is proposed, while in [23], augmented reality and a serious game are applied to engage a young audience with urban cultural heritage. For the proposed model, this makes it possible to distinguish gamification as a motivational layer from Serious Games as a more structured scenario for learning or training actions.

It is important that contemporary digital archaeology is increasingly moving toward the idea of a digital continuum. The CAA 2026 materials describe an approach in which archaeological knowledge passes from acquisition to processing, enrichment, and consultation of data [24]. In [25], it is shown how FAIR/LOD approaches, QGIS, Wikidata, and game logic can be combined in a learning environment. This confirms that contemporary digital solutions should not only accumulate data, but also make it understandable, connected, reusable, and suitable for different audiences.

An additional example can be taken from industrial AR solutions. VIEWAR ServiceAR combines indoor navigation, workflow instructions, checklists, a digital twin, and support for performing tasks in space [26]. This source is not part of the academic core of the article, but it demonstrates the practical logic of task-based interaction. For archaeology, this principle can be adapted carefully: not as a mechanical transfer of an industrial model, but as the idea of preliminary familiarization with an object, following a route, completing tasks, recording results, and preparing for real fieldwork.

Previous studies by the author have already addressed several elements that are important for this article. In [27], a distributed system for the development of AR cultural heritage projects using AI is considered, which creates a basis for a further transition to digital twins of archaeological objects. In the methodological work [28], the possibilities of interactive media and augmented reality in an educational course are shown. In [29], the use of generative AI in the management of projects for developing 3D models of game environments is examined. In [30], an approach to creating adaptive interactive multimedia spaces using artificial intelligence is proposed. Taken together, these results make it possible to connect the topic of digital archaeology with the broader logic of multimedia, adaptive, and immersive environments.

A comparison of the cited sources shows that individual components of a future information and analytical system are already being actively studied. There are works on 3D documentation and multi-sensor recording [1; 15], Gaussian Splatting and immersive heritage [2; 3], digital twins and IoT [4; 5], semantic data and Kompakkt [6–8], AI and machine learning in archaeology [9–14], educational 3D models [16; 17], archaeogaming, gamification, and Serious Games [18; 19; 21–23], as well as the digital continuum of archaeological knowledge [24; 25]. However, these directions are mostly considered separately.

An approach remains insufficiently developed in which an archaeological object is consistently transformed into a semantically enriched digital twin suitable for several modes of use at the same time: analysis, fieldwork planning, remote familiarization of the team with the object, learning, gamified interaction, immersive representation, and cultural tourism. It is this methodological gap that defines the logic of the present study and requires substantiation of an operational model in which digital recording, Gaussian Splatting, AI, semantics, gamification, and immersive scenarios do not exist separately, but work as interconnected components of an information and analytical system for archaeological heritage.

PURPOSE OF THE ARTICLE

The purpose of the article is to define the methodological foundations for using information and analytical systems to transform a digitally recorded archaeological object into a semantically enriched digital twin suitable not only for visual representation, but also for analysis, interpretation, planning of further research actions, learning, and immersive interaction with cultural heritage.

In this article, the digital twin is considered as an operational environment that combines the results of 3D recording, photorealistic representation, analytical recognition, semantic description, AI support, and user scenarios. This approach makes it possible to shift the focus from creating a separate digital copy of a monument to forming a system in which an archaeological object can be studied, enriched with knowledge, and used for preparing fieldwork, learning tasks, gamified formats, elements of Serious Games, and tourist and communication scenarios.

To achieve this purpose, the article sets the following tasks:

- to define the role of 3D recording, photogrammetry, LiDAR, laser scanning, and Gaussian Splatting in the digitalization of archaeological cultural heritage;
- to substantiate the feasibility of moving from a photorealistic 3D model to a semantically enriched digital twin of an archaeological object;
- to explain the importance of the analytical and semantic layers of the digital twin for object recognition, spatial navigation, fieldwork planning, and links with knowledge bases;
- to determine the possibilities of using AI support, gamification, Serious Games, and con-

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tinuous learning for educational and immersive interaction with archaeological heritage;
- to characterize the potential of the digital twin for cultural tourism, virtual routes, popular science communication, and remote access to archaeological objects.

The object of the study is the process of digitalizing archaeological cultural heritage under conditions of the development of information and analytical, immersive, and AI-supported technologies.

The subject of the study is the operational model of a semantically enriched digital twin of an archaeological object that combines 3D recording, Gaussian Splatting, analytical layers, semantic data, AI support, gamification, Serious Games, and tourist and educational interaction scenarios.

MAIN RESEARCH MATERIAL

The approach proposed in the article is based on viewing an archaeological object not only as a material monument that requires digital recording, but also as a basis for forming an operational digital environment. Such an environment should provide not only the visual representation of the object, but also work with data, context, analytical layers, semantic descriptions, planning scenarios, learning, immersive interaction, and cultural and tourist communication.

Within the study, the central element of the model is a semantically enriched digital twin of an archaeological object. It should be understood not as a static 3D copy of a monument, but as an integrated information and analytical model that combines the results of digital recording, photorealistic 3D representation, analytical recognition, semantic description, knowledge bases, user scenarios, and data updating mechanisms. Such a digital twin can be used for preliminary familiarization with the object, fieldwork planning, training of students and specialists, creation of virtual routes, and organization of immersive experience.

Structurally, a semantically enriched digital twin of archaeological heritage can be presented as a system of interconnected components:

$$T_A = \langle O, F, G, A, S, K, U, I, R \rangle, \quad (1)$$

where T_A is the semantically enriched digital twin of an archaeological object; O is the physical archaeological object or monument; F is the array of digital recording data; G is the photorealistic 3D representation, in particular based on Gaussian Splatting; A is the analytical layer; S is the semantic layer; K is the knowledge base; U represents user groups; I represents immersive interaction scenarios; R is the layer of data updating and quality control.

Formula (1) defines the general structure of the model, but it does not show how the digital twin is formed. Therefore, it is appropriate to describe it as the result of an integration transformation of heterogeneous data and functional layers:

$$T_A = f_{int}(F, G, A, S, K, U), \quad (2)$$

where f_{int} is the function of integrating digital recording data, 3D representation, the analytical layer, semantic description, the knowledge base, and user needs into a single operational environment.

The first stage in building such an environment is the digital recording of the archaeological object. It is not limited to one technical method and may include different data sources depending on the type of monument, its state of preservation, the accessibility of the territory, and the research purpose. In simplified form, the recording layer can be presented as follows:

$$F = \{P_h, L_s, L_D, V, GIS, IoT, D_f\}, \quad (3)$$

where P_h represents photogrammetric data; L_s represents laser scanning data; L_D represents LiDAR data; V represents photo and video documentation; GIS represents spatial and geographic referencing; IoT represents monitoring sensor data; D_f represents field documentation, notes, diaries, and other contextual records.

This representation emphasizes that a digital twin is not created from a single type of material. For an architectural object, laser scanning, photogrammetry, and GIS referencing may be important; for a cave complex, video documentation, spatial coordinates, and local observations may be important; for an object under threat of destruction, sensor data on the state of the environment may also be important.

After the recording stage, the data can be transformed into a photorealistic 3D representation. In the proposed model, Gaussian Splatting is not the starting point of digitalization, but a way of representing already collected data in a form suitable for immersive navigation, visual immersion, and further analytical enrichment. This transformation can be described as follows:

$$G = g_{GS}(P_h, V, L_s, L_D, GIS), \quad (4)$$

where g_{GS} is the function for forming a photorealistic Gaussian Splatting representation based on photogrammetric, video, scanning, and spatial data.

Formula (4) helps avoid the simplification in which Gaussian Splatting is presented as a self-sufficient replacement for all other methods of digital recording. Within the model, it is one of the ways of organizing and displaying the obtained data, and its value increases when the 3D scene is supplemented with analytical and semantic layers.

The analytical layer of the digital twin should ensure the transition from viewing the object to working with it. This involves identifying structural elements, areas of interest, damage, measurable parameters, navigation points, and changes in the state of the object. In general form, this layer can be presented as the result of processing the photorealistic representation while taking the semantic context into account:

$$A = g_A(G, S, K) = \{o_i, m_i, r_i, p_i \mid i = 1, ..., n\}, \quad (5)$$

where g_A is the function of analytical processing of the 3D scene; o_i represents recognized objects or elements of the monument; m_i represents spatial or morphometric measurements; r_i represents risks, damage, or signs of change in condition; p_i represents spatial positions, routes, or points of interest; n is the number of identified elements or analysis zones.

It is the analytical layer that makes the digital twin useful for research work. For example, in a digital environment it is possible to mark individual architectural elements, identify surface fragments, compare the condition of the object at different moments, formulate preliminary hypotheses about zones for further inspection, or prepare a field survey route.

However, analytical results must be linked to semantic description. For archaeology, it is not enough simply to identify an element in a digital scene. It is necessary to explain what kind of element it is, which typology it belongs to, which sources it is connected with, what its state of preservation is, and how it relates to other parts of the object. Therefore, the semantic layer can be presented as a structure of descriptions connected with analytically identified elements:

$$S = h_S(A, K, M) = \{(m_i, c_i, b_i, q_i) \mid i = 1, ..., n\}, \quad (6)$$

where h_S is the function of semantic description of analytically identified elements; M is the general set of metadata; m_i represents the metadata of a particular element; c_i represents a classification or typological description; b_i represents bibliographic, archival, or source links; q_i represents indicators of the quality, completeness, or reliability of the description.

Semantic enrichment makes it possible to transform a 3D scene into a knowledge environment. This is especially important for objects used not only by researchers, but also by students, museum professionals, specialists in digital heritage, tourism, and the wider public. The same fragment of a digital twin may have a scholarly description, a learning explanation, a tourist interpretation, and a gamified interaction scenario.

The symbols used in the operational model are presented in **Table 1**.

The proposed model is cyclical rather than linear. This is important for archaeology because each new survey, clarification, or interpretation may change the digital twin. After preliminary analysis, the team may carry out a new field visit, obtain additional materials, refine semantic descriptions, or revise hypotheses. Therefore, the digital twin should be updated rather than remain an unchanged visual model.

$$T_A(t+1) = U_r(T_A(t), \Delta F_t, \Delta A_t, \Delta S_t, \Delta I_t), \quad (7)$$

where $T_A(t)$ is the state of the digital twin at the current stage; $T_A(t+1)$ is the updated state of the digital twin; U_r is the updating function; ΔF_t represents new digital recording data; ΔA_t represents new analytical results; ΔS_t represents new or refined semantic descriptions; ΔI_t represents refined interaction or interpretation scenarios.

The cyclical nature of the model makes it possible to use the digital twin as a tool for preparation and for reducing unprepared physical intervention in the monument. Before a repeated visit to the object, the team can work with the digital model remotely: identify areas of interest, check preliminary hypotheses, distribute tasks, and create checklists and survey routes. In this case, the digital twin becomes a tool for organizing research work.

Planning the field stage can be described as the task of selecting a plan of action that reduces the time, resource, and physical intervention costs associated with the object without lowering the quality of the research. In simplified form, this can be presented as follows:

$$P^* = \arg\min_P [C(P) + \lambda R(P)], \quad \text{subject to } Q(P) \geq Q_{min}, \quad (8)$$

where P^* is the optimized fieldwork plan; P is a possible action plan; $C(P)$ represents the costs of time, resources, and organizational effort; $R(P)$ represents the risk of excessive or unprepared intervention in the monument; λ is the risk weight coefficient; $Q(P)$ is the expected quality of the research result; Q_{min} is the minimum acceptable quality level.

Formula (8) reflects the managerial logic of the model: the digital twin helps select a better justified work plan in which reducing intervention in the object does not contradict the quality of the research.

The operational function of the digital twin can be strengthened through IoT and sensor data. If an object requires monitoring of temperature, humidity, lighting, vibration, or other environmental

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Table 1

Symbols used in the operational model of a semantically enriched digital twin of archaeological heritage

Designation	Meaning of the designation	Functional role in the model
TA	Semantically enriched digital twin of an archaeological object	Central operational environment of the model
O	Physical archaeological object, monument, or archaeological site	Primary source of digitalization
F	Digital recording data	Basis for building the 3D representation
G	Gaussian Splatting or another photorealistic 3D representation	Visual and spatial basis for immersive interaction
A	Analytical layer	Recognition, segmentation, measurement, damage detection, and identification of areas of interest
S	Semantic layer	Metadata, typologies, sources, contexts, hypotheses
K	Knowledge base	Connection of the digital twin with scholarly data and external sources
P*	Optimized fieldwork plan	Minimization of unprepared intervention while preserving research quality
Iu	User scenario	Educational, gamified, tourist, or research interaction
R	Data updating and quality control layer	Updating the digital twin after new data and refinements

parameters, these indicators can enter the digital twin as a separate dynamic layer. In this case, the digital model supports not only analysis of the past state of the monument, but also current observation, risk detection, and preparation of preservation decisions.

The next level of the model is connected with user scenarios. One and the same digital twin can be used by different user groups, but for different purposes. For the researcher, accuracy, sources, hypotheses, and the possibility of repeated verification are important. For the student, a clear structure, tasks, and gradual immersion in the material are important. For the tourist, the route, storytelling, visual persuasiveness, and accessibility are important. This level can be formally presented as a function for creating an interaction scenario:

$$I_u = \varphi(T_A, L, G_m, T_o, U_u), \quad (9)$$

where I_u is the interaction scenario for a particular user group; φ is the function of adapting the digital twin to a specific scenario; L represents learning goals or continuous learning goals; G_m represents gamified mechanics; T_o represents the tourist and communication context; U_u represents the user profile or needs.

This makes it possible to combine scholarly, educational, museum, and tourist scenarios in one model without duplicating the digital object. What changes is not the digital twin itself, but the way it is presented, the level of detail, the set of tasks, navigation, the type of explanations, and the format of interaction with the user.

In the proposed model, gamification is not considered the main goal of digitalizing archaeological heritage. It should be interpreted as an additional motivational and communication layer. This may include virtual routes, hints, object searches, levels of difficulty, interactive tasks, or scenarios for engaging students, tourists, and museum visitors. Gamification helps make interaction with the object more active, but it should not simplify or distort the scholarly content.

Elements of Serious Games have a somewhat different character. They can be used to model learning or professionally oriented situations: following a route through the object, finding the required zone, determining the type of an element, recording an observation, filling in a form, or preparing a preliminary conclusion. In this format, the digital twin becomes not only a viewing environment, but also a learning space for task-based learning.

Industrial AR solutions demonstrate a useful logic of task-based interaction. In such systems, the user can move through space using indoor navigation, receive tasks, complete checklists, and record the result with a photo, text, or confirmation form. For archaeology, this logic can be adapted carefully: not as a direct transfer of a production model, but as a principle of preliminary familiarization with an object, route preparation, completion of learning or research tasks, and recording of results in a digital environment.

Cultural tourism is another important direction for using semantically enriched digital twins. Not all archaeological objects can be opened for mass physical visitation. Some of them are fragile, remote, dangerous, or insufficiently prepared for visitors. Virtual routes, immersive scenes, and gamified explanations make it possible to increase the visibility of such objects without creating excessive physical pressure on the monument.

The general logic of the proposed operational model is shown in **Fig. 1**. Unlike linear schemes, in which a digital resource moves from creation to use, this model has a cyclical character. At the center is the semantically enriched digital twin, and around it are formed the contours of recording, 3D representation, analytical enrichment, semantic interpretation, fieldwork planning, learning, gamification, tourist communication, and data updating.

In the proposed scheme, the digital recording contour provides the initial acquisition of data about the object. The 3D representation contour is responsible for creating the spatial and photorealistic scene. The analytical contour provides recognition, segmentation, measurement, and detection of changes. The semantic contour connects digital elements with metadata, sources, typologies, and knowledge bases. The planning contour uses the digital twin to prepare fieldwork, while the educational and tourist contour provides immersive, gamified, and popular science interaction scenarios.

The practical implementation of the model can be carried out in stages. At the first stage, an archaeological object is selected and the purpose of digitalization is defined: preservation, research, learning, museum presentation, or tourist communication. At the second stage, the digital recording of the object is carried out. At the third stage, a 3D or Gaussian Splatting representation is formed. At the fourth stage, analytical and semantic layers are added. At the fifth stage, the digital twin is used for planning, learning, immersive interaction, and popularization. After new field actions, the model is updated, which ensures its cyclical development.

Thus, the operational model of a semantically enriched digital twin makes it possible to combine several functions that are often considered separately. It supports digital preservation, scholarly analysis, fieldwork planning, educational training, gamified interaction, Serious Games, cultural tourism, and remote access to archaeological objects.

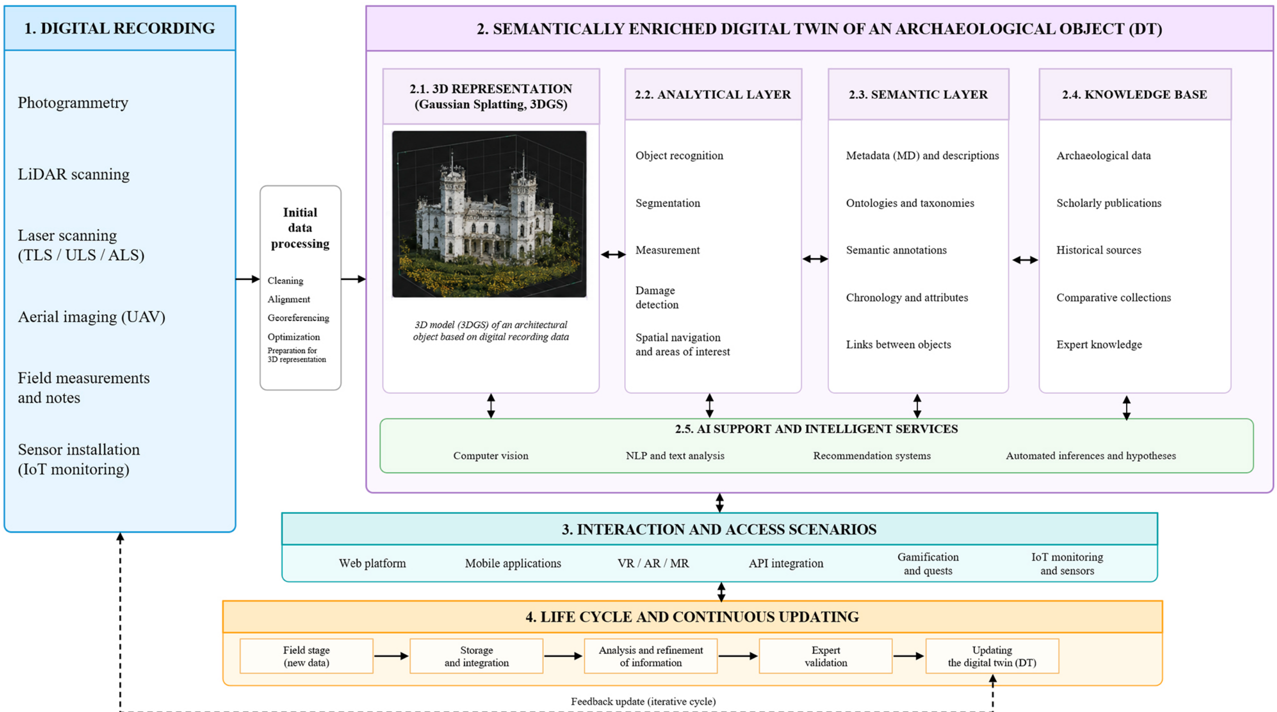

Fig. 1. Cyclical model for using a semantically enriched digital twin of archaeological heritage

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Its advantage lies not in replacing archaeological expertise, but in creating a structured digital environment that makes work with the object more prepared, explainable, and reusable.

For the university environment, this model has additional value because it can be used to train archaeology students, museum professionals, specialists in digital heritage, multimedia technologies, tourism, and interdisciplinary teams. It creates conditions for continuous learning, in which work with archaeological heritage takes place not only during physical presence at the object, but also in a digital environment where routes can be repeated, details analyzed, tasks completed, interpretations compared, and preparation made for the next stages of research.

The proposed model does not replace field methods, professional interpretation, or expert responsibility. Its purpose is different: to make the digital model of an archaeological object more suitable for analysis, learning, planning, communication, and responsible interaction with cultural heritage. This is the main difference between the information and analytical approach and the simple creation of a digital copy of a monument.

CONCLUSIONS

The study has shown that the digitalization of archaeological cultural heritage cannot be limited only to the creation of digital copies of artifacts, monuments, or archaeological landscapes. The current stage of development of digital archaeology requires a transition from isolated 3D models to information and analytical systems in which digital recording, 3D representation, semantic enrichment, artificial intelligence, immersive technologies, and user scenarios function as interconnected components. This approach makes it possible to consider an archaeological object not only as something to be visualized or preserved, but as a basis for forming an operational digital environment.

The article substantiates the feasibility of using a semantically enriched digital twin of an archaeological object as the central element of such a system. Unlike a static 3D copy, the digital twin combines the results of photogrammetry, LiDAR scanning, laser scanning, aerial photography, field measurements, sensor data, Gaussian Splatting, analytical layers, metadata, knowledge bases, and AI support. As a result, it can be used not only to demonstrate an object, but also for its analysis, interpretation, spatial navigation, planning of further research actions, and gradual updating after new field stages.

The role of Gaussian Splatting in the digitalization of archaeological heritage is defined separately. This technology is promising not only as a means of photorealistic 3D representation, but also as a basis for forming an immersive environment that can be used in research, educational, and communication scenarios. At the same time, the article emphasizes that the potential of Gaussian Splatting is fully realized only when it is combined with analytical and semantic layers: object recognition, segmentation, measurements, damage detection, spatial areas of interest, metadata, ontologies, taxonomies, and expert knowledge.

The proposed operational model makes it possible to present the digitalization of an archaeological object as a cyclical process. First, digital recording and preliminary data processing are carried out; then a 3D representation and a semantically enriched digital twin are formed; after that, the twin is used in scenarios of access, analysis, learning, gamified interaction, and cultural tourism. New field data, observation results, refined hypotheses, and expert validation return to the system and update the digital twin. This logic ensures not a one-time creation of a digital model, but a continuous life cycle of work with archaeological heritage.

The practical value of the proposed approach lies in the possibility of preliminary familiarization of the research team with the object, identification of areas of interest, preparation of survey routes, distribution of tasks, and reduction of the number of unprepared physical interventions in the monument. This is especially important for fragile, partially destroyed, remote, or access-restricted archaeological objects. In this case, the semantically enriched digital twin serves not only as a data archive, but also as a tool for planning, preparation, and decision support.

The educational potential of the model is connected with the possibility of using digital twins in the training of archaeology students, museum professionals, specialists in digital heritage, multimedia technologies, and tourism. In such an environment, the user can not only view the object, but also complete learning tasks, follow virtual routes, work with hints, analyze individual elements of the monument, and gradually immerse themselves in the archaeological context. In this model, gamification is considered a means of increasing engagement, while elements of Serious Games are considered a tool for task-based learning and preliminary preparation for work with the object.

The tourist and communication potential of semantically enriched digital twins is also defined. They can be used to create virtual routes, popular science explanations, remote access to archaeological objects, preliminary familiarization with monuments, and more responsible cultural tourism. This makes it possible to increase the visibility of archaeological heritage without excessive physical pressure on objects, which is important for preserving monuments and expanding access to them for different user groups.

Thus, information and analytical systems in archaeology should be considered as a tool for moving from digital recording to a full immersive experience. The proposed model combines the technological, analytical, semantic, educational, and communication levels of work with archaeological heritage. Further research may focus on practical testing of the model on specific archaeological or architectural objects, developing quality criteria for the semantic enrichment of digital twins, evaluating the effectiveness of gamified and Serious Games scenarios, and integrating such systems into curricula, museum practices, and digital tourist services.

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ІНФОРМАЦІЙНО-АНАЛІТИЧНІ СИСТЕМИ В АРХЕОЛОГІЇ ЯК ІНСТРУМЕНТИ ЦИФРОВОЇ ЕКОСИСТЕМИ КУЛЬТУРНОЇ СПАДЩИНИ ТА ІМЕРСИВНОГО ДОСВІДУ

Резюме. *У статті розглянуто інформаційно-аналітичні системи в археології як інструменти цифровізації культурної спадщини для формування імерсивного досвіду. Обґрунтовано, що сучасна цифрова археологія має переходити від створення окремих 3D-копій артефактів, пам'яток або археологічних ландшафтів до побудови семантично збагачених цифрових двійників, придатних для аналізу, планування, навчання, популяризації та дистанційної взаємодії. У межах такого підходу цифрову фіксацію об'єкта за допомогою фотограмметрії, лазерного сканування, LiDAR, фото- та відеоданих, ГІС-прив'язки й сенсорних даних розглянуто як початковий етап формування цифрового середовища. Gaussian Splatting визначено як перспективний інструмент фотореалістичного 3D-представлення археологічного об'єкта, що може бути доповнений аналітичними шарами розпізнавання, сегментації, вимірювання, виявлення пошкоджень, просторової навігації та семантичного опису.*

Запропоновано операційну модель семантично збагаченого цифрового двійника археологічної спадщини, у якій поєднуються 3D-фіксація, Gaussian Splatting, ШІ-підтримка, бази знань, цифровий сторітелінг, гейміфікація, елементи Serious Games, continuous learning і сценарії культурного туризму. Такий цифровий двійник може використовуватися не лише для візуального представлення пам'ятки, а й для попереднього ознайомлення дослідницької команди з об'єктом, планування польових робіт, визначення зон інтересу, розподілу завдань, підготовки маршрутів обстеження та зменшення кількості непідготовлених фізичних втручань. Окрему увагу приділено можливості використання цифрових двійників у підготовці студентів-археологів, музейників, фахівців із цифрової спадщини, мультимедійних технологій і туризму, а також у створенні віртуальних маршрутів, навчальних завдань, науково-популярних сценаріїв і форм віддаленого доступу до археологічних об'єктів.

Ключові слова: *інформаційно-аналітичні системи, цифрова археологія, культурна спадщина, цифровий двійник, Gaussian Splatting, 3D-фіксація, семантичне збагачення, штучний інтелект, імерсивний досвід, гейміфікація, Serious Games, continuous learning, культурний туризм.*

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