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Between technical history, industrial archaeology, Digital Humanities and Virtual Reality
A digital corpus of a former industrial site under rehabilitation: the case of CAP 44

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Abstract

This article introduces interdisciplinary research on digitizing industrial heritage, focusing on CAP44 in Nantes, a rare 19th-century reinforced concrete structure. The building, being transformed into the "Cité des imaginaires," is documented using CIDOC-CRM ontology, Omeka-S, and GraphDB to enable digital twin modeling. The AIDEN VR platform allows immersive 3D exploration of historical data via gestures, movement, and voice. This innovative tool enhances understanding and promotes digital access to complex heritage. The project also raises ethical and methodological issues, aiming for transparent and rigorous digital preservation of industrial memory.

CCS Concepts

• *Human-centered computing*
• *Information systems → Information retrieval → Users and interactive retrieval*
• *Applied computing → Arts and humanities*

1.Introduction

This article highlights interdisciplinary research undertaken to digitize heritage and promote knowledge capitalized for museums experts and historian professionals. It demonstrates how Digital competencies can help humanities and social science to better understand the historical legacy of our heritage.

First the research context is exposed. Next, the scientific proposition is detailed: it is named AIDEN which is a VR tools dedicated to historian experts: objectives, programming and operating. This is followed by a use case demonstrating the application and opportunities of using such semantic digital twin for history.

One of the key challenges this research addresses is the increasing misalignment between domain experts' knowledge - particularly in history and heritage - and the complexity of semantic technologies and data visualization tools used in digital preservation.

2. Research context

In Nantes, scientific research on digital heritage is conducted within the LS2N Laboratory (UMR CNRS 6004) as part of its cross-disciplinary research theme, *Creation, Culture, and Digital Societies*, in collaboration with the François Viète Center Laboratory (UR CNRS 1161). Those two laboratories have worked together for over 20 years on the development of a history of science and technology in relation to engineering. Together, they founded a federated research group called EPOTEC (Study of Processes and Technical Objects): www.epotec.fr.

This research group carries out projects in the field of advanced industrial archaeology. Objective is to combine historical understanding and the preservation of industrial and technical heritage through the tools of engineering science. The underlying assumption is that an industrial object—whether historical or contemporary—remains an industrial object. It may be a mass-produced product, a unique artisanal piece, a machine or tool used in its design or manufacture, or even a complete factory and its full industrial process studied in detail. In every case, contemporary engineering tools can be mobilized to document, preserve, and promote our technical heritage.

Our team has developed expertise in a wide range of methods and technologies, such as 3D laser scanning, reverse engineering, knowledge capitalization, semantic databases, and virtual tools, among others. We collaborate with numerous museums, institutions, and companies seeking to preserve their historical

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knowledge. We are also founding members of the 3D Consortium of TGIR Huma-Num (https://shs3d.hypotheses.org), which has produced the White Paper on Best Practices for 3D in the Humanities and Social Sciences [BldCL*21] and contributed to the creation of the French national repository of 3D humanities data: https://3d.humanities.science

These projects are inherently interdisciplinary, combining engineering, history, ontology design, computer science, and heritage studies to build shared tools for digital knowledge production.

3. Designing AIDEN: a VR tool dedicated to historical studies

3.1 Objectives

In the humanities, a widening gap persists between content experts (e.g., historians) and the technical frameworks of data representation such as ontologies and knowledge graphs. AIDEN was specifically designed to reduce this epistemological and practical divide.

Knowledge graphs based on ontology standards are powerful tools for data sharing, representation, expression and analysis, but they pose significant challenges in terms of consistency checking, navigation and interaction. Traditional 2D interfaces often fail to provide an intuitive user experience. In this case, only a data visualization expert can deal with the content of the graph. Historians are excluded from these practices. In our field of application, consistency checking cannot be limited to automated validations such as shape constraint (SHACL). Information can be true from a logical point of view (when it satisfies the constraints of the ontology), but false from a historical point of view. Then, human-readable content is needed to monitor data quality. This requires the involvement of content experts, the historians in our case. AIDEN aims to facilitate the involvement of historians in the revision of knowledge graphs.

AIDEN is a system based on virtual reality (VR) to provide an immersive and intuitive application for exploring, analyzing, and modifying knowledge graphs in an interactive three-dimensional environment. It has been designed toward management of historical data with historians. Two objectives had been defined:

- Knowledge Capitalization: AIDEN seeks to enhance knowledge capitalization and decision-support processes by making technical data readily accessible to non-experts
- User-Centered Design: The system is designed to facilitate physical navigation of virtual space and optimize user experience through multi-modal interactions

AIDEN offers an interface with voice control and two navigation modes. One of these takes advantage of the large 3D space in the virtual environment to combine close inspection and global overview.

3.2 AIDEN Proposal

VR training applications have demonstrated an efficient and interactive way of learning and processing new information [DUW*22]. While many experiments rely on realistic environment in industrial context [DTM*20], we deal with data representations. AIDEN (Artificial Intelligence for Data Exploration and Navigation) is a system designed to interact with knowledge graphs in a 3D immersive virtual reality (VR) environment (figure 1). This approach takes advantage of humans' innate ability to interact with three-dimensional environments, thereby enhancing the user experience by reducing cognitive load while exploiting the potential of a third dimension for data visualization purposes.

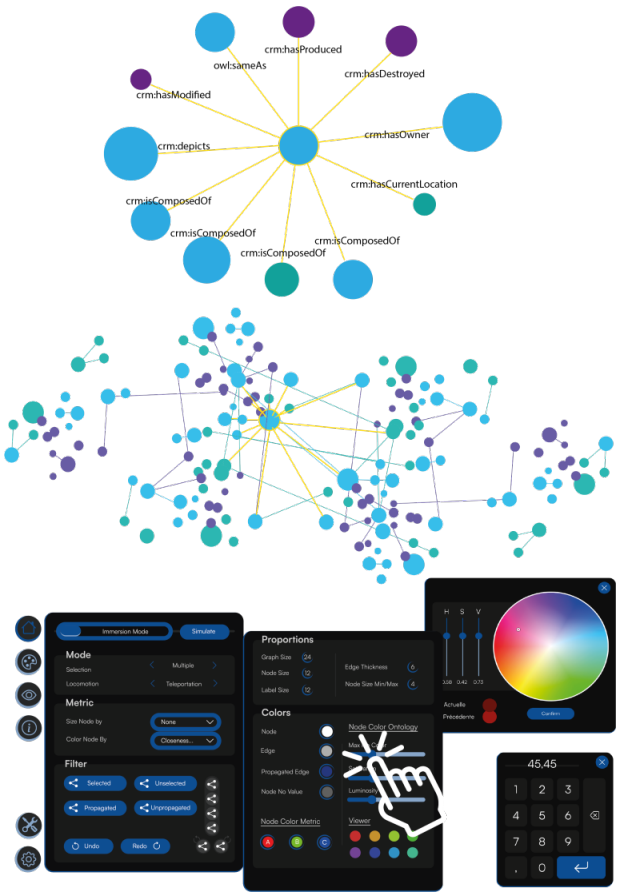

Figure 1: *AIDEN schema of the main UX: In the foreground are the UIs for editing the graph, in the middle is the filtered 3D graph, with the selected node(s) highlighted, and in the background is a detailed 2D graph layout made up of the selected node(s) and their first degree of relationships.*

Building data visualization charts is a common and powerful way of reading the content of a knowledge graph. Many works such as Li's one [LWZ*22] are helpful in this sense and offer a complementary approach to AIDEN, which dives into a low-level representation of the data.

The use of 3D graphs in virtual reality (VR) for data visualization has been a topic of interest in recent years. TGView3D [MKR20] highlighted the challenges posed by the size of graphs, which can contain thousands of nodes and an order of magnitude more edges. They suggested the use of three dimensions as a solution, providing more space to organize the graph. In 2008, Ware and Mitchell [WP08] also emphasized the benefits of 3D graph visualizations, noting that visualizing information structures can lead to easier interpretation. They found that 3D viewing using stereo and motion depth cues significantly increased the size of the graph that could be displayed and read.

AIDEN incorporates an interface with voice control to overcome both the difficulties of writing queries and the limitations of software menu displays. In fact, we believe that 2D user experience (UX) overlays should be reassessed for the VR environment. Users can express their requests verbally.

3.3 Implementation

Apart from history and heritage, many disciplinary fields face the same duality of "content experts vs. data visualization experts", with the same technological standards (RDF) and the same amount of data to supervise.

Indeed, RDF technologies for data management are widely used in many fields such as biological interactions, industrial performance assessment or global information integration, building information modeling, etc.

The emergence of industry 4.0, driven by digital data, connectivity, and cyber-systems, brings the industrial issues closer to the RDF solution and tools.

Development of the 3D environment was carried out with Unity game engine. The knowledge graph (historical data) is managed in the Ontotext GraphDB tripleStore. GraphDB also provides the SPARQL endpoint and the API. Knowledge graphs are built with CIDOC-CRM as core ontology, handling most of the semantics. Additional high level ontologies provide a standard environment (RDFS, OWL, DCterms, etc.). Some other domain specific ontologies such as RDAA refine the description when needed.

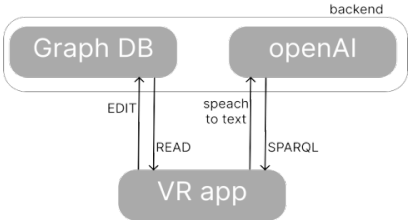

Figure 2: *global architecture of AIDEN*

The back-end functionality of the voice interface leverages OpenAI APIs (Figure 2). Whisper is used for the Voice-to-Text conversion and cognitive processing is done by ChatGPT.

The application is built and tested with HTC vive focus 3 virtual reality headsets.

The underlying data is modeled using RDF triples, and the system is optimized to display graphs containing between 100 and 800 nodes (representing approx. 500–4000 triples). This range accommodates most use cases encountered in historical knowledge modeling. Below 100 nodes, traditional 2D tools remain effective; beyond 800 nodes, performance and clarity deteriorate in VR.

It is important to note that AIDEN focuses on data record visualization and editing, not on ontology engineering. While the semantic logic of the ontology (inheritance, transitivity, etc.) is leveraged for reasoning, it is not exposed to the user. The purpose is to offer historians a tool to explore and validate human-written historical records, which may originate from heterogeneous sources and contain inconsistencies or modeling errors.

By providing such an environment, AIDEN bridges the gap between content expertise and semantic technologies, empowering historians to directly engage with complex data in a way that respects both technical rigor and intuitive usability.

4.Use case: CAP44, also known as the Great Mills of Nantes

The central aim of this work is not the valorization of a single industrial site, but rather to propose a scalable methodology that reconnects domain experts with the technical ecosystems of semantic web technologies. One single heritage site is detailed here in order to demonstrate how AIDEN empowers experts to engage directly with knowledge graphs - bridging the gap between domain knowledge and semantic infrastructures. The immersive digital platform can address the methodological blind spot in many heritage projects: enabling non-technical experts to critically explore, validate, and edit structured historical data themselves.

The research has been demonstrated through the use case called CAP44 building in Nantes (France). Originally built as the Usine de la Piperie by architects Lenoir and Etève and engineers in the late 19th century, CAP44 represents one of the earliest large-scale reinforced concrete industrial structures used for the first time the large scale the Hennebique process patented in 1892. Transformed into offices in 1972, CAP44 remains an essential artifact of industrial and architectural innovation due to the rarity of surviving similar structures.

This site, initially featuring Europe's largest industrial steam engine at the time, exemplifies pioneering construction methods and embodies significant technical heritage demanding careful preservation. Thus, CAP44 is also representative of broader questions in industrial heritage studies, particularly in regard to the digital preservation and reinterpretation of post-industrial landscapes [STR20]. Numerous studies in industrial heritage

emphasize the need for systematic documentation and digital mediation of endangered technical sites [DAU80] [TIC12]. These approaches promote not only the conservation of physical structures, but also the representation of industrial processes and societal transformations that accompany them.

Figure 3: *CAP44 before rehabilitation*

4.1. Historical description

The former Great Mills of Nantes, likely the oldest large-scale reinforced concrete building still standing in the world. The site's history remains largely unknown. In 1894, Paul Perraud purchased the land and commissioned the construction of the Usine de la Piperie, a vast steam-powered flour mill, which was renamed CAP44 during its transformation into office space in 1972. The building was designed by Nantes-based architects Lenoir and Etève, in collaboration with Sée engineers from Lille (North of France), concessionaires of the Hennebique reinforced concrete process. The choice of reinforced concrete addressed the recurring fire hazards common in flour mills. This heritage structure is of great interest in the history of technology for several reasons:

- CAP44 is currently the oldest surviving industrial building of this scale made from reinforced concrete. All the few similar structures had been demolished. It is the unique witness of a construction technique that revolutionized the field—complete with engineering offices, patents, transformed materials, and industrial processes.
- CAP44 was a pioneer in the development of industrial flour mills. In 1892, roller milling machines replaced traditional millstones in France, dramatically increasing productivity and allowing centralized production powered by large steam installations. At the turn of the 20th century, the Usine de la Piperie housed the largest steam engine in any French mill, featuring an 8.4 meters flywheel, the largest of its kind in Europe at the time.
- Today, CAP44 presents an important heritage case. It reflects the evolution of labor and industrial space in France, having been heavily altered in 1972 to become an office building. Its preservation remains a subject of debate among the people of Nantes. Although recent municipal decisions support its rehabilitation, public opinion is still marked by a significant lack of knowledge among those opposed to its conservation. This situation highlights the urgent need for heritage mediation.

In partnership with the Heritage Department of Nantes Métropole, sources had been gathered. It includes corporate, departmental, and regional archives, as well as personal data collections from Nantes residents, such as those from Nantes Patrimonia (https://patrimonia.nantes.fr), the Nantes city's heritage wiki.

The site is currently undergoing a planned rehabilitation, funded by Nantes Métropole Urban Community, with the objective of transforming CAP44 into a public venue: the "Cité des Imaginaires", which will also house the future Jules Verne Museum (https://metropole.nantes.fr/cite-imaginaires). See figure 4.

Figure 4: *The future « Cité des imaginaires" (Neutelings Riedijk Architects and ARS French company)*

Moreover, accordingly to all contemporary documentation—study reports, archaeological excavations, core sampling, technical analyses, architectural documents, etc.—is being integrated into this corpus to create a meaningful digital twin of the building.

4.2. Knowledge capitalization

Focusing on the first part of life when the building was a flour mill, thanks to interdisciplinary studies with many specialties: history, archives, archaeo-architecture, archaeo-engineering… we gathered many information's (figure 5).

Then it was possible to understand how the flour mill was operating and to draw the space process for producing flour. Figure 6 below illustrates the process positioning main steps of the industrial engineering transformation.

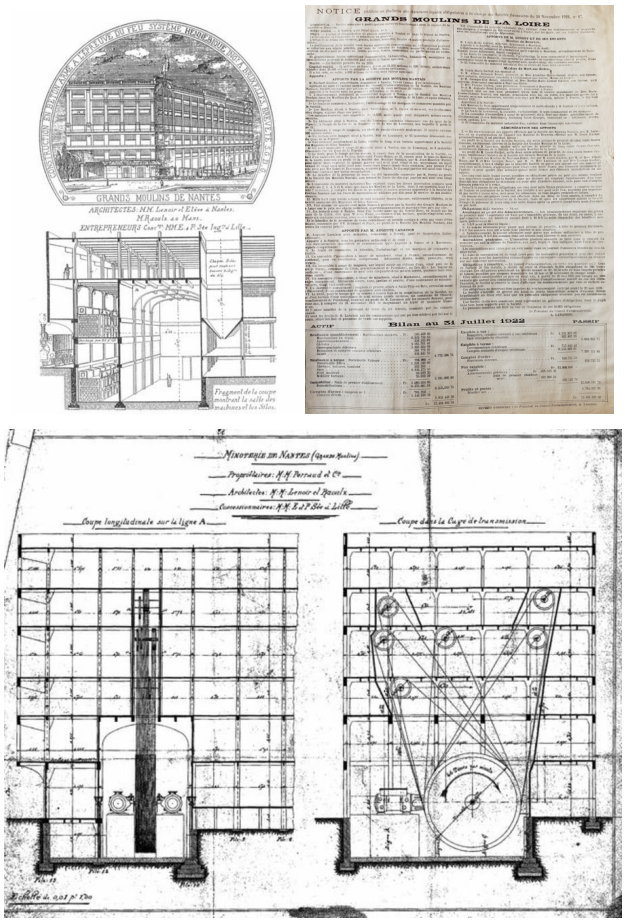

Figure 5: *Some historical archives of the former Great Mills of Nantes*

The collected data is modeled using standard ontologies (mainly CIDOC-CRM), stored in an Omeka-S database, and published on a GraphDB triple store. This initial framework enables a first comparison between the historical sources and the intended data modeling approach. Figure 7 represents the database model. Historians can access data directly to the online database: https://epotec.univ-nantes.fr/s/cap44

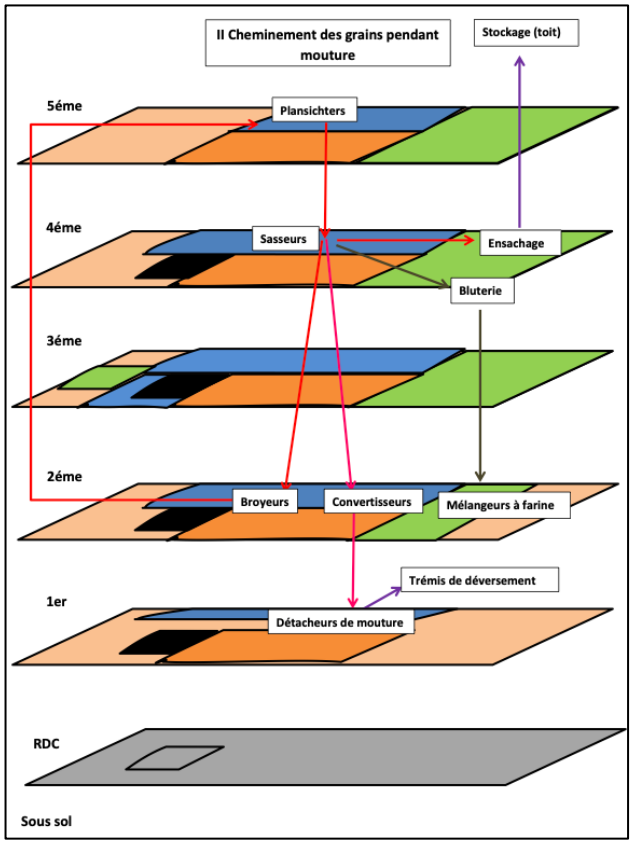

Figure 6: *Industrial engineering analysis*

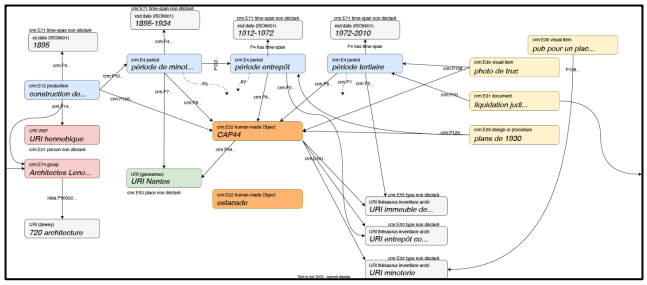

Figure 7: *Database model*

Ultimately, with the entire digitized corpus and in collaboration with Nantes Métropole, an application will be developed to enable in-situ visualization of virtual data on interactive touch panels, tablets, or smartphones.

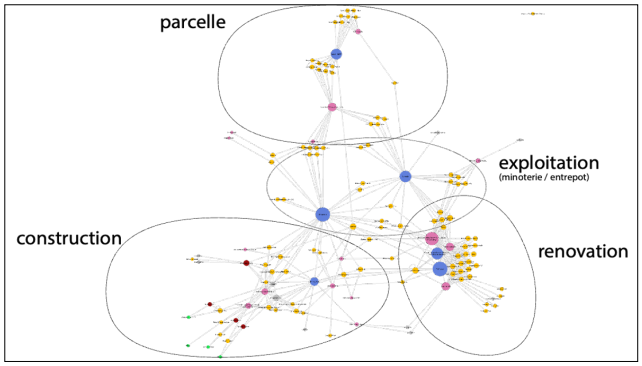

Figure 8: *Digital content*

4.3 Immersive knowledge access

In order to demonstrate the power of such technologies, our scientific team has led to the development of an innovative tool, AIDEN, an immersive VR platform allowing historians to visualize knowledge graphs in three-dimensional spaces. Integrating physical navigation with multimodal interactions (gestures, movements, and voice commands), AIDEN makes complex historical data accessible.

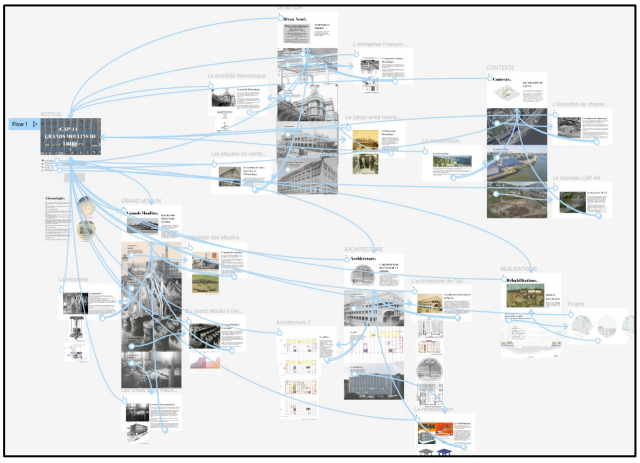

Figure 9: *AIDEN: navigating through the data*

Two distinct representations of the knowledge graphs were designed to optimize navigation and user experience:

- The first, referred to as the *"global view"*, supports pattern recognition and group identification.
- The second, the *"immersive view"*, allows users to dive into the graph, offering a more localized perspective that enhances the readability of relationships between individual nodes.

Together, these digital tools support the construction of a multi-layered heritage narrative, combining a detailed understanding of the evolution of industrial processes and practices with the analysis of a built structure that exemplifies major architectural and technical innovations of the late 19th century. The ultimate aim is to move from academic research to broad opportunities for public engagement and cultural valorization, such as museum integration.

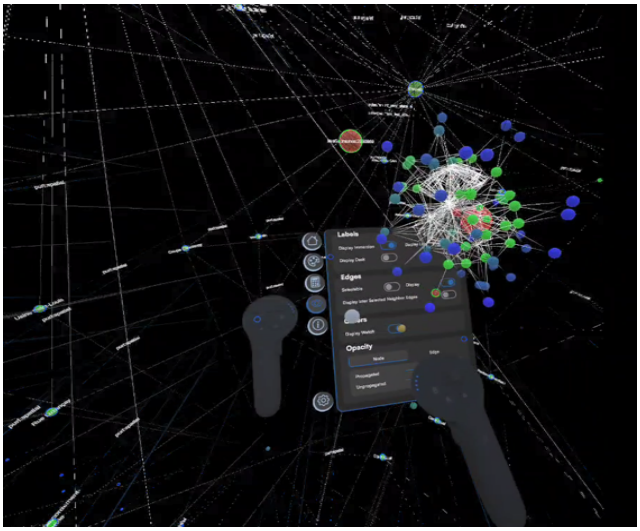

Figure 10: *AIDEN: immersive visualization*

Beyond demonstration, AIDEN aims to be integrated into the professional routines of heritage specialists. In the CAP44 project, the tool has been introduced to local heritage experts for early-stage feedback. For these users, AIDEN could enhance everyday tasks such as validating historical narratives, correcting inconsistencies in archival records, or preparing materials for exhibition interpretation. It supports a shift from static data consultation toward interactive exploration and validation, making semantic databases more usable for non-technical actors in cultural institutions.

5. Conclusion and perspectives

5.1 AIDEN tool

AIDEN is an innovative tool designed to provide an immersive and intuitive experience for exploring, analyzing, and modifying RDF knowledge graphs in a 3D virtual reality environment. It has been applied on the French mills: the potential for analyzing heritage data using the graphDB triple store of the historical OMEKA-S data base. AIDEN is open source and interoperable with any type of RDF BD.

In future work, a dedicated evaluation phase is planned in collaboration with local heritage professionals and museum

experts. The objective will be to assess the tool's usability, cognitive impact, and contribution to daily workflows. Criteria such as user autonomy, error detection capability, and perceived usefulness in exhibition planning or historical validation will be studied. This evaluation will help determine AIDEN's added value and refine its user-centered design for real-world adoption in digital heritage practices.

5.1 Impact for experts' decision-support

AIDEN stands as an original contribution to digital humanities methodologies: it is both a technical innovation and a response to a clear user need, structured to empower historians and heritage professionals in navigating semantic data without requiring technical expertise. The system demonstrates how interdisciplinary collaboration can lead to intuitive, immersive environments that reconnect content expertise with structured digital knowledge.

Our research underscores significant epistemological issues, challenging traditional heritage methodologies to achieve more accurate and authentic digital reconstructions. By bridging historical analysis with cutting-edge digital modeling and AI technologies, the team strives for ethically sound and transparent preservation, interpretation, and dissemination of industrial heritage.

Video of AIDEN

This link provides a video showing AIDEN in action: https://youtu.be/XQoHTOq2Iwc?si=7gjzwWi_D9AE6cyF

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