

EU-DOCS for SmUCS

CO-SUPERVISED SUBJECT PROPOSAL FOR A DOCTORAL CONTRACT

Title of the thesis project Knowledge-Driven Generative AI for Precise Reconstruction of Coastal Historical Buildings via Digital Twin Modelling	
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Main research field: Computer Science Secondary Research Field: Civil Engineering	
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Scientific description of the research project Scientific context Coastal historical buildings are invaluable cultural assets, representing centuries of architectural heritage, social history, and engineering ingenuity. However, these structures face increasing threats from natural and human-induced factors, including climate change, rising sea levels, saltwater intrusion, and extreme weather events. Without effective preservation and restoration strategies, many of these buildings risk irreversible deterioration, leading to the loss of both historical significance and structural integrity. This thesis aims to address these challenges by leveraging advanced digital twin modeling, generative AI, and knowledge-driven approaches to reconstruct and preserve damaged coastal historical buildings. Digital twins provide a virtual replica of these structures, enabling continuous monitoring, predictive analysis, and informed decision-making for conservation efforts. By integrating generative AI and knowledge graphs, this research seeks to enhance the accuracy of reconstruction models, simulate degradation patterns, and propose sustainable restoration solutions. The findings of this study will contribute to the broader field of Cultural Heritage (CH) conservation, offering innovative methodologies for protecting historical buildings in coastal environments. The research will also support policymakers, engineers, and conservationists in developing proactive strategies to mitigate future risks and ensure the longevity of these architectural landmarks.	
Scientific objectives The primary objective of this thesis is to develop an innovative approach to preserving coastal historical buildings by integrating knowledge from the European Cultural Heritage Cloud (ECCCH), generative AI, and digital twin modeling. The research will first establish a structured knowledge graph to represent multimodal historical data and architectural details from historical photographs, paintings, news archives, private letters, and literature. Generative AI will then be employed to reconstruct damaged or missing architectural elements, using historical archives and datasets. A digital twin will	

be created to simulate real-time damage assessments and deterioration patterns, helping to predict the impact of coastal hazards such as sea-level rise, extreme weather, and saltwater intrusion. The study aims to propose sustainable restoration strategies that preserve the authenticity of these structures while incorporating predictive maintenance and resilient materials. Through the validation of these methodologies on real-world case studies, the thesis will provide valuable insights and digital tools for cultural heritage conservation, contributing to the long-term protection and management of coastal historical buildings. As part of this research, a modular and interoperable platform will be developed to manage, visualise, and compare multiple digital twin models of coastal historical buildings. This platform will support version control, semantic annotation, and integration of heterogeneous datasets (e.g. 3D models, point clouds, metadata, historical archives), enabling collaborative work among researchers, heritage professionals, and local stakeholders. The system will be designed to comply with FAIR data principles and adopt open standards (e.g. CityGML, IFC, Linked Data) to ensure long-term accessibility and reusability. A key objective is to enable seamless integration with the ECCCH, contributing structured data and AI-generated reconstructions to a broader European infrastructure for cultural heritage preservation, analysis, and dissemination.

Scientific challenges

Digital Twins offer a powerful tool for researchers and conservationists in cultural heritage to predict deterioration, simulate restoration techniques, and plan sustainable preservation strategies [1]. Beyond conservation, they serve as interactive platforms for public education and virtual tourism, fostering inclusive access to heritage sites that may be geographically distant or physically inaccessible. Photogrammetry is a popular method in heritage modelling, but more and more works in heritage modelling are using laser scanning [2], GIS and especially Building Information Modelling (BIM) techniques, ontologies and 3D computer graphics [3]. This type of work is critical for historical buildings in geographical areas with high seismic risk [4]. While immovable monuments are easy to locate, movable artefacts such as archival maps, manuscripts, old prints, works of art etc. are easily moved from one place to another, so their relation to geographic space and 3D models of buildings is more changeable in time [5]. This issue is even more challenging when representing entire collections as spatial narratives within 3D models of buildings. The need to semantically represent narratives has been addressed but only in the context of digital libraries [6].

Knowledge Graphs (KGs) [7] provide a structured framework for integrating and analyzing diverse datasets, making them a key enabler for data investigation across various domains, including law, CH [8,9,10] and Digital Humanities [11]. By representing entities and their relationships as interconnected nodes and edges, KGs offer a natural and intuitive way to model and interpret complex real-world phenomena. In the CH domain, KGs enable the integration of heterogeneous datasets into a unified model, improving interoperability and accessibility [12]. They also enhance transparency and traceability by providing clear reasoning pathways and provenance tracking, crucial for scholarly research. Furthermore, KGs facilitate narrative construction by visualising relationships among historical figures, events, and artifacts, allowing researchers to build and validate hypotheses. Despite their potential, implementing KGs in CH faces significant challenges, such as difficulties in linking unstructured data, ontology and entity alignment, and maintaining data quality in multimodal and multilingual datasets [13].

The construction of KGs involves integrating information from multiple heterogeneous sources into a coherent domain-specific representation. This process entails aligning ontologies and schemas across datasets and resolving entities to identify and link records representing the same real-world object. The challenges are amplified in CH contexts by the multi-modal and multi-lingual nature of the data [13]. While KG construction for textual and visual data has seen some advancements, most existing research focuses primarily on integrating textual and visual data, leaving other modalities relatively underexplored [14].

Methodology

The methodology of this PhD thesis follows a knowledge-driven approach to enable the precise reconstruction and simulation of coastal historical buildings using Generative AI and Digital Twin Modelling. First, multimodal data (historical documents, architectural plans, 3D scans, GIS data, and material studies) will be aggregated and structured into a unified knowledge graph, integrating information from the Cultural Heritage Cloud. This enriched knowledge base will provide contextual and structural insights essential for accurate reconstructions. A critical aspect of KG construction is revisability, which allows users to refine and correct integrated data over time. Mechanisms to detect weak signals or errors introduced during Information Extraction (IE) are essential for ensuring trustworthiness¹⁵. Incremental approaches for ontology and entity alignment further enhance consistency by accommodating new entities without disrupting existing structures. Quality assurance

is another cornerstone of KG construction, involving the evaluation, detection, and resolution of quality issues. Collaborative validation with domain experts can improve accuracy, while use cases like recommendations may tolerate reduced quality for efficiency. Ensuring high data quality, especially in CH, is vital for preserving historical accuracy and interpretability. Handling uncertainty remains a significant challenge in KG construction. Historical and cultural datasets often include ambiguous or incomplete information, necessitating systems that integrate confidence levels, provenance tracking, and differing viewpoints. Distinguishing well-documented facts from less certain interpretations is crucial for maintaining the reliability and scholarly utility. Second, Generative AI models, trained on historical and architectural datasets, will generate high-fidelity 3D reconstructions of the buildings, ensuring historical accuracy while filling gaps in incomplete or deteriorated structures. Third, a Digital Twin model will be developed to dynamically link the reconstructed buildings with real-world environmental data, allowing for interactive visualisation and analysis. Finally, degradation simulations will be conducted by integrating climate, erosion, and material decay models, enabling predictions of long-term structural changes and supporting conservation strategies. This methodology bridges AI-driven generative modeling with cultural heritage research, providing a scalable and data-rich framework for preserving vulnerable coastal historical sites. Specific coastal historical buildings^{16,17} will be considered as application use cases.

Expected results

The expected results of this thesis include the development of a robust framework for the digital preservation and restoration of coastal historical buildings. It is anticipated that the integration of knowledge graphs with generative AI will lead to highly accurate reconstructions of damaged or missing architectural elements, offering a valuable tool for conservationists and architects. The digital twin models are expected to provide a dynamic, real-time representation of the buildings, enabling the simulation of various degradation scenarios and the identification of key vulnerabilities. These models will also allow for predictive maintenance and early detection of potential damage, ensuring proactive conservation efforts. The research is expected to demonstrate that AI-driven restoration techniques, when combined with sustainable materials and strategies, can effectively balance historical authenticity with the need for modern preservation practices. Ultimately, the results will contribute to the field of cultural heritage preservation, providing actionable insights and digital tools that enhance the protection of coastal historical buildings in the face of climate change and environmental challenges.

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PhD student profile and skills required

The ideal applicant should possess the following qualifications and competencies:

Master's degree (or equivalent) in Computer Science, Civil Engineering, Digital Heritage, or a closely related discipline.

Proven experience in AI/ML, particularly in generative models (e.g., GANs, diffusion models, transformers), with practical knowledge of relevant frameworks such as TensorFlow or PyTorch.

Familiarity with 3D reconstruction, point cloud processing, and Building Information Modelling (BIM); experience with tools such as Blender, Autodesk Revit, or Rhino.

Strong programming skills in Python; familiarity with C++ or JavaScript is a plus.

A foundational understanding of digital twin concepts, IoT integration, and semantic data modelling in built environments.

Familiarity with geospatial analysis tools (e.g., QGIS, ArcGIS) and remote sensing data integration for environmental or heritage applications.

Interest or background in architectural conservation, cultural heritage studies, or coastal/maritime heritage.

Strong written and verbal communication skills, with the ability to work effectively in an interdisciplinary and collaborative research environment.

Scientific alignment with EU-DOCs for SmUCS objectives

The proposed PhD thesis aligns closely with the scientific orientations and strategic priorities of the EU-DOCs for SmUCS (Smart Urban Coastal Sustainability) programme. It addresses several core objectives through a multidisciplinary approach that integrates Artificial Intelligence, Digital Heritage, Built Environment Modelling, and Coastal Urban Sustainability.

The thesis leverages generative AI and digital twin technologies to support sustainable decision-making in coastal urban environments. By digitally reconstructing endangered historical buildings, it contributes to the digital preservation of cultural assets and informs sustainable urban development strategies in heritage-sensitive coastal zones. This directly supports SmUCS' aim to foster digital innovation for smarter, more resilient urban coastal systems. In addition, the research adheres to Green AI principles by emphasizing computational efficiency, model transparency, and environmental responsibility. Lightweight generative architectures, energy-efficient training methods, and the use of pre-trained models and transfer learning will be prioritized to minimize the carbon footprint of AI processes.

The project bridges architecture, computer science, geospatial technologies, and cultural heritage—mirroring the SmUCS emphasis on interdisciplinary, cross-sectoral research. The integration of domain knowledge with AI-generated models enables novel reconstruction methods that preserve cultural identity while applying advanced computational methodologies, fostering scientific innovation.

By creating detailed digital twins, the thesis supports the proactive monitoring, assessment, and protection of vulnerable heritage assets. This aligns with the SmUCS focus on enhancing climate resilience and risk-informed urban planning for coastal communities. The digital twin framework proposed in this project also contributes to data-driven governance and planning, enabling public authorities and stakeholders to simulate restoration scenarios, track deterioration, and prioritize interventions. The knowledge graph and AI components further enable semantic interoperability and intelligent querying, supporting smarter heritage asset management in urban policy frameworks.

Societal and economic challenges and contributions

The proposed PhD research addresses key societal and economic challenges by developing AI-driven digital twin technologies for the preservation and reconstruction of coastal historical buildings, which are increasingly threatened by climate change and urban development. By enabling cost-effective, high-fidelity digital reconstructions, the project supports sustainable heritage conservation, enhances climate resilience, and contributes to the long-term safeguarding of cultural identity and community cohesion. Economically, it stimulates innovation in the growing heritage-tech sector, opening new opportunities for digital tourism, education, and urban regeneration.

Partnership context

Siren Analytics Using AI, automation and advanced search, Siren links data from open source, vendors and classified sources allowing investigators to surface and analyze risks, threats and crimes for the national security, public safety, fraud and compliance, and cyber threat communities. Due to privacy and security concerns, public datasets are rarely available for experimentation, therefore the vast datasets available in the cultural heritage domain could fill this gap.

Communauté d'Agglomération de La Rochelle through the "pôle développement numérique responsable" have a direct interest in this thesis that is in alignment with their Responsible Digital Strategy, as confirmed by David BERTHIAUD. The project's focus on knowledge-driven generative AI and digital twin modelling for the precise reconstruction of coastal historical buildings directly supports La Rochelle's ambitions for low-carbon, climate- resilient urban development and heritage preservation.



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