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A digital ecosystem for the multidisciplinary study of Notre-Dame de Paris

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Abstract

The 2019 fire of Notre-Dame de Paris was not only a significant event in its history, but also provided a unique platform for multidisciplinary studies and digital data analysis. At the initiative of the CNRS and the Ministry of Culture, a large-scale collaboration is currently underway to manage and analyse the extensive data generated in connection with the restoration of the cathedral. The role of digital data is crucial for understanding complex multidisciplinary studies, especially in the field of cultural heritage. A digital data working group, composed of thirty scientists from 12 laboratories, is focused on documenting and organising this collective experience to serve both the immediate needs of restoration and the long-term goals of cultural heritage research. Key challenges include data traceability, knowledge modelling, multidimensional analysis and the need to address gaps in semantic understanding, memory, data correlation and technology. To address these challenges, a novel method is proposed that combines the digital representation of material heritage with the evolving knowledge about it. By collaborating with the wider scholarly community involved in Notre Dame's scientific action, the aim is to introduce new methods in heritage research and bridge the gap between the humanities and digitally-driven scholarship. This initiative also intersects with two primary scientific vectors: the technological approach to data collection and the generation and analysis of semantically enriched datasets.

Keywords : heritage science, digital ecosystem, computational modelling, digitisation

1. The pivotal role of digital data in the study of Notre-Dame through a multidisciplinary lens

The fire that devastated Notre-Dame de Paris on 15 April 2019 marked a new chapter in its history, but also provided a unique opportunity to observe and study a monument that faces the challenges of disaster as a global, interdisciplinary, diachronic and heuristic site. Within the framework of the CNRS (National Centre for Scientific Research) and Ministry of Culture initiative for the restoration of the Cathedral [1; 2], all the scientific and technological challenges involving dozens of disciplines related to the study and restoration of the Cathedral are focused on one fundamental problem: the management of huge amounts of data generated by collective efforts and encompassing numerous disciplines, themes and methods, all focused on the same object of study in a comprehensive and cross-sectional analysis. This is an unprecedented opportunity to examine the way in which each discipline, coming from its own field, is confronted with the test that permeates all disciplines [3]. The role of digital data is now central to developing new semantics to understand the intricacies of multidisciplinary studies. This is especially true for cultural heritage, where complexity is not limited to the physical properties of tangible objects, but also extends to the mechanisms of knowledge production that give them their identity as knowledge objects and their meaning as heritage. The juxtaposition of tangible objects and multidisciplinary studies provides an excellent milieu to explore the collective analysis and interpretation of facts, objects and phenomena that unite the creation of data and knowledge in the field of heritage science. The main objective of the Digital Data Working Group [4], which includes about thirty scientists from 12

research laboratories, is to answer the question: how can this collective experience be documented, organised and made accessible to meet the needs of different users, both in the short term (in relation to the study of the cathedral during restoration) and in the long term (oriented towards building a knowledge base for heritage conservation)?

2. Addressing gaps in data traceability, knowledge modelling and multi-dimensional analysis

To contextualise this challenge in the scientific literature, it is essential to summarise the various aspects of a fragmented progress in the digitisation of cultural heritage.

A predominant problem concerns the traceability and interoperability of digital data creation processes. In this environment, the data produced are often influenced by instrumentalisation constraints and cognitive processes that are poorly traceable, requiring a detailed understanding of their origin and nature [5; 6; 7].

Another challenge is the formalisation of knowledge models, a task that requires the observation and analysis of practises in different disciplines [8], especially in the field of cultural heritage [9]. More recently, graph-oriented databases have been introduced to enable rapid navigation through datasets and their semantic relationships [10; 11].

Beyond simply classifying data as "digital entities", a key challenge of this project is to enhance them by explaining the content they convey, especially through semantic annotation methods. In addition to texts, images and videos, 3D images and especially realistic 3D reconstructions have become indispensable for the digitisation of cultural heritage, especially in the field of archaeology, conservation and restoration [12; 13].

The recent move towards large-scale production of spatially representable 3D images and models, which further facilitates 4D acquisition and visualisation [14], has raised new issues related to the management of large amounts of data and their semantic enrichment, as well as their automatic classification for research purposes [15; 16; 17].

Several works by CNRS-MAP have focused on the intersection of the above issues, using methods to semantically structure and link 2D, 3D and 4D representations for heritage applications [18; 19; 20]

This overview identifies four major gaps that need to be addressed:

- A semantic gap: Although there is widespread but fragmented production of digital resources on cultural heritage objects, the growing amount of uninterpreted data highlights the urgent need for inventive methods aimed at the central production of semantically enriched digital resources.
- A memory gap: Despite the advances that have been made in the field of knowledge engineering in aggregating and enhancing data, the application of these techniques remains a challenge. This is mainly due to numerous subjective decisions, implicit research protocols, little formalised knowledge and highly personalised cultural heritage skills.
- A data correlation gap: If some research provides a framework for aggregating observations around a heritage object represented in 3D/4D, how can we create autonomous linking mechanisms between these resources?
- A technological gap: How can we tightly link the production and collaborative analysis of multidisciplinary resources to a physical site, ensuring a sustainable balance between human activity and computational support?

3. Building a cathedral of digital data and multidisciplinary knowledge

As an experimental platform for building a decentralised, flexible and open sociotechnical system inspired by the idea of ecosystem-centred architecture [21; 22], our methodology focuses on digitisation, not only of the physical aspects of a cultural asset, but also of the knowledge used to understand it. With this in mind, we aim to introduce an innovative mechanism that combines a dynamic digital representation of a tangible cultural asset (similar to a digital twin [23; 24]) with the representation of the knowledge that evolves around the object (similar to the methods for scientific knowledge geographies [25]). The aim is to investigate the intertwining of the spatial, temporal and morphological attributes of a cultural object with the knowledge structures developed by researchers in the course of their academic work. Based on groundbreaking n-dimensional techniques for data acquisition, analysis and correlation, the spatial, temporal and semantic distribution of the multi-layered documentation and analysis will be recorded and investigated within the framework of an interdisciplinary study. Following deep mapping [26; 27], the aim is to link data, observation and analysis procedures with the interpretation and description of different aspects of a single tangible entity, navigating through a realm of digital assets that are inherently a complex interplay between tangible entities, actor networks, their relationships and configurations.

With the dual aim of archiving and evaluating different points of view on an identical cultural heritage, this project fuses conceptual modelling techniques with different facets of digital humanities and computer science. The aim is to create a collaborative knowledge system [28], a digital ecosystem that reveals a rich layer of information, shaped by people and organised in a methodical way.

Our working group is taking advantage of the unique opportunity to digitally accompany the creation of a representative dataset. In collaboration with the extensive scientific consortium committed to the Notre Dame initiative (175 researchers from 50 laboratories), our working group aims to make some innovative contributions to the science of cultural heritage more broadly:

- A digital record of a shared journey: We seek to bring together and secure the digital embodiment of a "collective journey". This has implications for digital development in heritage studies and a deep understanding of the connections that link each participant, academic cluster or discipline to the multi-layered intricacies of a heritage artefact.
- A paradigmatic collection of heritage conservation data: This unprecedented reservoir of interlinked data and knowledge has the potential to trigger a high-profile dynamic in terms of the creation and dissemination of methodologically ordered resources that encompass all specialisations when considering a single object from a heritage perspective.
- A replicable endeavour: Our project paves the way for subsequent efforts in relation to other cultural properties. It promotes the adoption of comprehensive methodologies by providing innovative templates for comprehensive comparative assessments of heritage-related academic institutions and placing digital information at the heart of strategies to rejuvenate collaboration in interdisciplinary academic fields.
- Connecting academics with heritage attributes via heritage science data: From an analytical standpoint, our project leads to wide-ranging investigations into the intricate relationships researchers form with their objects of study. Future tools for synergistic data exploration could help develop new scenarios for the social emergence of research consortia that include strategies for cultivating academic networks based on the organic alignment of skills and passions that extend to non-academic domains.

4. Bridging humanities and digitally driven science through methodology and technology

Our approach is based on the seamless integration of scientific, methodological and technological dimensions at the intersection of digital humanities, cultural heritage research and informatics.

From a scientific perspective, our goal is to introduce n-dimensional data correlation techniques. The aim is to collectively generate, organise and evaluate vast amounts of diverse data focusing on four key elements: (i) space – realised through the 3D spatial representation of routinely generated digital data related to the topic under investigation, (ii) form – realised through annotation, classification, identification of relevant features and the careful management of related concepts representing them within terminological and ontological frameworks, (iii) time – realised through (tool-based or cognitive) monitoring activities of themes and data, complemented by the longitudinal study of forms and spatial aspects, and (iv) domain of knowledge – illuminated through the study of thematic overlaps arising from the myriad "disciplinary lenses" sharpened on particular areas of interest.

From a methodological perspective, our focus is on documenting and understanding scholarly endeavours that focus on a multidisciplinary theme. This includes illuminating the ways in which different stakeholders generate, apply and link digital data in relation to their objects of study. The aim is to decipher the character of the knowledge invoked, its particular characteristics in relation to each academic discipline, and its conceptual and functional links to the spatial, temporal and structural attributes of the objects under study.

On a technological level, our endeavour manifests itself in the development of a digital ecosystem: a transparent socio-technical construct comprising (i) a collaborative toolkit for human-directed acquisition, classification and annotation of digital resources that facilitates supervised machine learning and guides the design of (ii) an autonomous system responsible for the continuous expansion and integration of the dataset, strengthened by the automated dissemination of spatial, temporal and shape features (such as the geometric and visual properties of materials, objects, spaces etc.) is strengthened).

The rare prospect of collaboratively curating and evaluating large-scale digital datasets on a representative heritage theme can be truly harnessed through close collaboration with the many scholars embedded in the overarching scholarly narrative of Notre Dame. This goal can only be achieved if the unique opportunity presented by the cathedral's restoration is transformed into a collaborative project. The aim is to stimulate an introspective discourse on the rejuvenation of working methods, thus laying the groundwork for pioneering tools and techniques for the field of heritage conservation.

Tracing multidisciplinary crossroads through data methodologies

In close collaboration with all the thematic working groups of the Notre Dame Scientific Initiative and the main actors of the restoration work — those overseeing the tasks related to the structural assessments of the monument, the archaeological excavations and the cataloguing and study of the remains — the Digital Data Working Group is working on the intersection of two primary scientific vectors.

The first vector ranges from the digital record to the technological implementation of methods for data collection, enrichment and linkage. The second vector, on the other hand, which intersects with the first, is concerned with the methods for generating and evaluating the coming wave of semantically enriched datasets. It is based on two key case studies in the context of Notre Dame's

comprehensive restoration project: (i) the wooden roof (often referred to as the 'forest'), which attracts researchers interested in materials (such as wood and metal), construction methods, timing and structural dynamics; (ii) the collapsed vaults, which combine studies of materials (such as stone and metal), archaeology (construction nuances, lapidary signs), architecture (design, geometry) and structural and acoustic behaviour with more intangible elements such as heritage emotions.

This special issue of the journal contains three articles from the Digital Data Working Group presenting the ongoing efforts and initial results of this methodology. The first article deals with the creation of a digital platform for the centralisation and preservation of multidisciplinary scientific data. The following articles deal with multi-temporal 2D/3D data fusion for morphological analysis of the collapsed vaults and virtual reconstruction of the roof structure from multiple sources.

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