2025

SOCIETAL IMPACT STUDY

Notre-Dame scientific project

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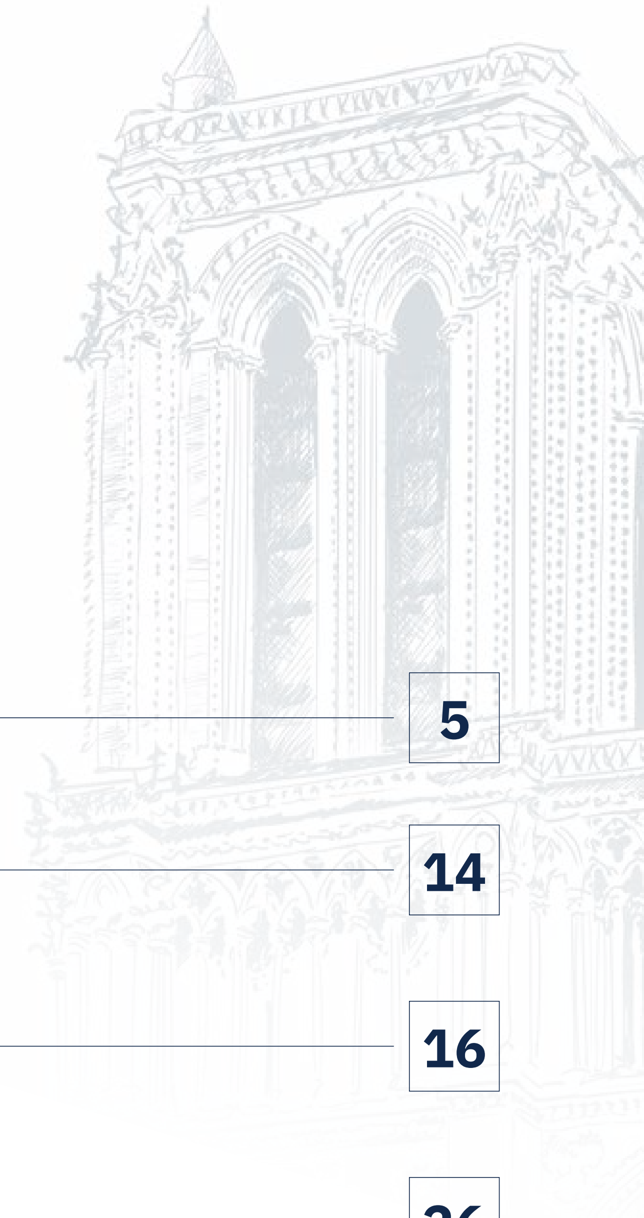


EXECUTIVE SUMMARY

EXECUTIVE summary

OBJECTIVES

The objective of the impact study of the Notre-Dame scientific project is not only to assess the scientific project in terms of its initial ambitions, but above all to analyze the societal impact of this unprecedented cooperation between science and restoration.

On the one hand, it explores how this collaboration has impacted scientists, restoration professionals, and citizens in their practices and understanding of heritage and science.

On the other hand, it examines what has made it possible to establish or bring together converging interests which, if encouraged, will have further effects on all of these actors and on society.

Finally, it assesses the role of the CNRS (and its academic partners) and its cooperation with the Ministry of Culture in the deployment of a scientific project and the responses thus provided to a heritage crisis.

METHODOLOGY

The impact study was conducted from January to March 2025. This study consisted of:

1

DEFINING THE PRECISE CHRONOLOGY OF THE NOTRE-DAME SCIENTIFIC PROJECT, from the development of the knowledge mobilized to the reopening of the cathedral **(deliverable 1)** ;

2

PRECISELY ANALYZING THE DIFFERENT STAGES OF THE IMPACT PATHWAY, i.e., the path from knowledge to effects on society, namely the "Input" or resources mobilized, the "Output" or scientific outputs, the "Intermediaries" or actors who appropriate a research product to transform it, and the "Impacts" or effects on society **(deliverable 2)** ;

3

DERIVING AN IMPACT RADAR IN THE VARIOUS SOCIETAL DIMENSIONS (cultural, environmental, social, political and regulatory, economic, health) **(deliverable 3).**

To this end, this study was based on all available written documentation (bibliography, activity reports, information provided by scientists), audiovisual material (including online symposiums on the scientific project), and digital material, as well as a series of 21 semi-structured interviews with scientific actors and intermediaries.

This document has been reviewed and revised by the stakeholders consulted.

MAIN FINDINGS

This study clearly demonstrated the ability to mobilize scientific knowledge and methods in response to a societal crisis and within very tight deadlines.

In addition to the long-standing cooperation with the Ministry of Culture and the mutual trust that fostered the joint scientific project, this responsiveness is due to **four major factors that are characteristic of the CNRS:**

1 **THE ACCUMULATION OF FUNDAMENTAL AND APPLIED KNOWLEDGE** over the long term;

2 **THE VERY BROAD SPECTRUM OF DISCIPLINARY AREAS** and fields of expertise mobilized;

3 **THE ABILITY TO RESPOND TO A CRISIS,** which changes scientific priorities, while respecting the principle of academic freedom;

4 **THE CAPACITY TO COORDINATE AND MOBILIZE** academic partnerships throughout the country.

This scientific project has made it possible, on the one hand, to put the available knowledge in heritage sciences at the service of the restoration of Notre-Dame and, on the other hand, to take advantage of privileged access to the cathedral to renew the body of knowledge. It is thus possible to distinguish between the work that supported the restoration project, the work that will be used for future projects, and the outputs that are intended for audiences other than those involved in the restoration. Finally, some of the work has made it possible to renew knowledge without any predictable short-term use (i.e., not linked to any impact other than scientific at this stage).

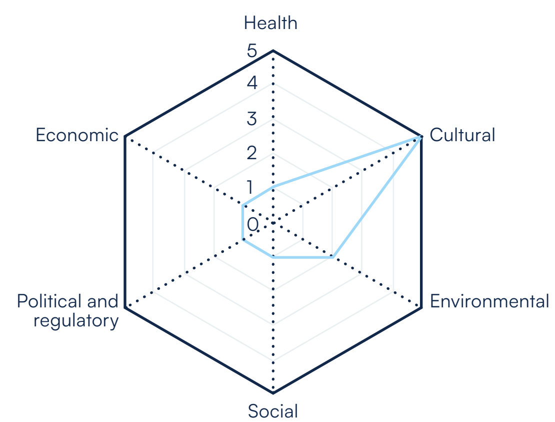
The Notre-Dame project is unique in that it brought together scientists and restoration experts in the same place at the same time. This daily interaction between the communities of science and heritage restoration has encouraged the restoration experts and the media (project owners, restoration project managers, engineering firms, restoration companies, the City of Paris, and the media) to take ownership of and transform the knowledge gained from the scientific project. ■■■

■■■ This close cooperation, combined with intensive communication with all audiences, has also made it possible to open up new perspectives for other stakeholders who will be able to exploit and build on them (training establishments, experimental medieval building sites, the future Notre-Dame Museum, insurers).

The diversity of these "intermediaries" has led to proven, expected, or hoped-for impacts in various societal dimensions. **The major impact** of this scientific project is revealed in **the cultural sphere,** through scientific contributions to the evolution of the theoretical framework and practices of heritage restoration, and through the development of new narrative modalities that promote the opening of heritage culture to a wider audience. This renewed perception of heritage is already informing conservation policies **(political impact)**. Finally, the scientific project has contributed to enhancing the value of restoration professions, increasing their attractiveness, and initiating a necessary reflection on the training of all stakeholders, with the need to combine academic knowledge, architectural and historical knowledge of buildings, and the know-how of craftsmen and journeymen **(social impact).**

The work carried out and its transformation by intermediaries has also led to the development of more sustainable restoration practices (reuse or use of more environmentally friendly materials, establishment of short supply chains, and sustainable resource management), which therefore have a significant **environmental impact.** In addition, the scientific project has shed light on the implementation of monitoring processes for pollution emitted by historic monuments, revealing a **health impact** that is currently limited to the Paris region but could extend to the whole country. More unexpectedly, there is a clear **economic impact,** both in terms of the revenue generated by the many heritage mediation projects carried out as part of the scientific project and the potential development of a new construction sector using freshly cut timber. The research conducted on the materials used in restoration (freshly cut timber, lead, etc.) could lead to **regulatory changes** in building standards.

Impact radar



Finally, this project has been an opportunity to structure heritage sciences, demonstrate the cross-cutting role of digital technology, and strengthen cooperation between the CNRS (and its academic partners) and the Ministry of Culture **(Scientific Impact).** This scientific momentum will be continued and expanded with the creation of the MAESTRO thematic network ("Understanding the challenges of major monuments: MAtEriaux, STRuctures, EnvirOnnements"), whose achievements will undoubtedly amplify or concretize the impacts observed or expected in this study.

In conclusion, it should be noted that this scientific project was marked by a remarkable collective dimension, which was essential to its success. **All those involved, whether scientists or restoration professionals, shared the feeling of participating in an exceptional human adventure, characterized by intense cooperation and strong personal involvement in the service of a common heritage.**

The Notre-Dame construction site has a unique feature for bringing together scientists and restaurateurs in one place at the same time.

TIMELINE

April 15, 2019
Fire

December 2024
Reopening

METHODICAL REMOVAL AND SORTING OF RUINS AND DEBRIS

DIAGNOSIS - SECURITY - CONSOLIDATION

RESTORATION SITE

1995

Knowledge production

April 2019

Removal of furniture, treasures, paintings

APRIL 16-19
- Continuation of removal
- Transport to the Louvre
- Inventory
- Visual assessment
- Start of securing

APRIL 18
Creation of the Association of Scientists at Notre-Dame de Paris restoration service

APRIL 24-25
Removal of the paintings from the upper room, the carpets, and the Virgin and Child

APRIL 26
Creation of a CNRS Task Force

May 2019

2 MAI
Law project for organizing the restoration of the Cathedral

MAY 4
Meeting between the Ministry of Culture and CNRS. Creation of GTs

June 2019

JUNE 13
First meeting of the working groups. Establishment of the scientific project

JULY 29
Adoption of Law No. 2019-803 for conservation and restoration and establishing a national subscription

July-December 2019

NOVEMBER 28
Decree establishing the public institution responsible for conservation and restoration

DECEMBER
Start of access to the Notre-Dame for scientists

2020

JUNE 2020
Overall health assessment of the building

OCTOBER 19-20, 2020
Scientific workshop symposium at INHA

2021

MARCH 2021
Presentation of the diagnosis

SEPTEMBER 2021
Final securing and consolidation

MARCH 28-29, 2022
Inter-working group seminar

2024

APRIL 22-24, 2024
Symposium on the Birth and Rebirth of a Cathedral

2025

Preview of the Notre-Dame Museum

MAESTRO Interinstitutional Thematic Network

IMPACT PATHWAY

CONTEXT

April 15, 2019: Notre-Dame fire

SCIENTIFIC CHALLENGES:

1 **SUPPORTING** the restoration project

2 **RENEWING** the corpus of knowledge about Notre-Dame

Outputs that fed into the intermediaries

INPUT

CNRS/MITI MINISTRY OF CULTURE
- Establishment of the Scientific Project
- Addendum to the Framework Agreement, establishment of agreements
- Funding (MITI, Ministry of Culture)

4 COORDINATORS 9 WORKING GROUPS
- Structure, Stone, Wood, Metal, Glass and Stained Glass, Monumental Decor, Emotions and Mobilizations, Acoustics, Digital
- 180 scientists (20% CNRS)
- Approximately 80 laboratories (including 50 CNRS)

FINANCING
- €8.5 million own resources (ANR, Europe, etc.)
- €40 million payroll

MOBILIZATION of knowledge and skills accumulated by stakeholders over 30 years

OUTPUT

WORK THAT ACCOMPANIED THE RESTORATION OF NOTRE-DAME
- Surveys (digital, manual, etc.) before and after the fire
- Post-fire diagnosis
- Materials for restoration
- Lead alterations and pollution tracing
- Acoustic studies
- Construction of exceptionality and registers of sacredness

WORK FOR OTHERS CONSTRUCTION SITES (including Notre-Dame)
- Digital cathedral
- Post-fire structural assessment of historic buildings
- Characterization of wood and framework for identical reconstruction
- Sound recording of trades and the construction site
- Studies of the monumental decor of Notre-Dame
- Interaction of surface deposits with stained glass windows and review of criticism regarding the authenticity of the stained glass windows

OTHER SCIENTIFIC PRODUCTIONS
- Recording of the site's audio and visual memory, material memories, collective or individual memories
- Coming to Notre-Dame: experiences and perceptions
- Acoustic digital twins at different periods
- Radio drama podcast and audio guide

100% SCIENTIFIC WORK
(listed in Appendix 3)

INTERMEDIATE

PROJECT OWNER: NOTRE-DAME ET DRAC PUBLIC INSTITUTION

ARCHITECTS IN CHIEF OR ACMH

ENGINEERING FIRMS

RESTORATION COMPANIES

EXPERIMENTAL BUILDING SITES
(Guédelon, Guyenne)

EDUCATIONAL INSTITUTIONS
(INP, Chaillot, engineering schools, universities, guilds, etc.)

CITY OF PARIS

MEDIA
(TV, radio, print media, social media)

FUTURE MUSEUM FOR NOTRE-DAME

INSURERS

IMPACTS

SCIENTIFIC IMPACT
- Structuring heritage sciences
- MAESTRO network
- Role of digital technology
- Strengthening cooperation between the CNRS and the Ministry of Culture

CULTURAL IMPACT
- Restoration of cultural heritage
- Access to cultural heritage for all

ENVIRONMENTAL IMPACT
- More sustainable catering practices

SOCIAL IMPACT
- Training for heritage restoration professionals
- Attractiveness of the professions

POLITICAL AND REGULATORY IMPACT
- Inform conservation policies
- Taking heritage perception into account in projects
- Evolution of building standards

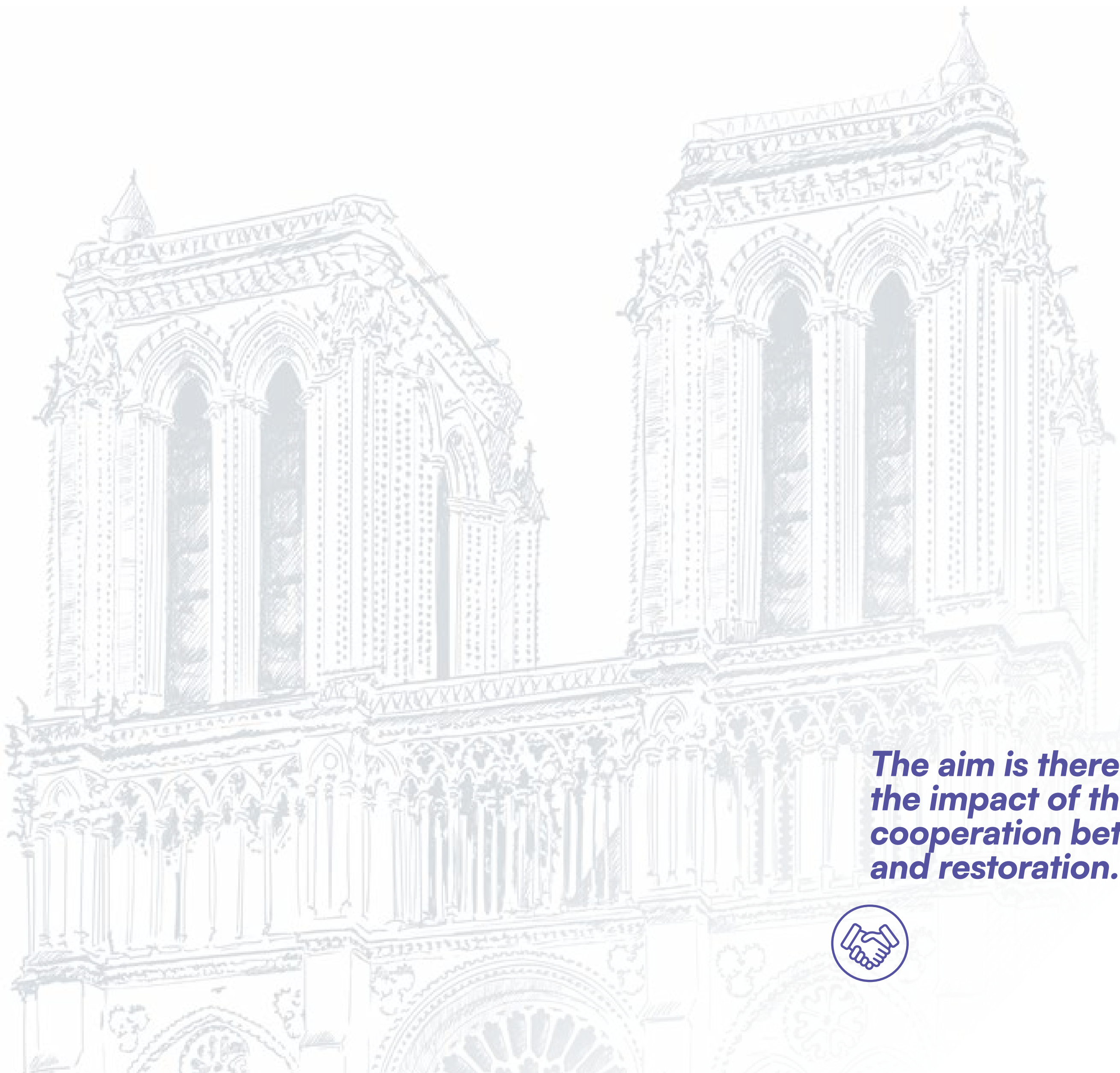
ECONOMIC IMPACT
- Revenue from heritage mediation
- Green wood industry

HEALTH IMPACT
- City of Paris action plan against lead pollution
- Monitoring of historic monuments

INITIAL external context

April 15, 2019, 6:55 p.m., Notre-Dame de Paris is on fire!

The emotion felt by everyone in France and around the world led scientists from all disciplines, specialists in heritage, to come together almost immediately to form an association dedicated to the restoration of the cathedral, with the support of the Ministry of Culture and the CNRS, and the desire to learn more about Notre-Dame in order to restore it better. Under the leadership of the chief architects of historic monuments in particular, the laboratories of the Ministry of Culture, which were hard at work from the very first days (LRMH, C2RMF), as well as INRAP and the archaeology department of the DRAC Ile de France, established a precise protocol for handling the rubble, later reclassified as remains, an invaluable source of material for future research. To structure the efforts and skills involved, the CNRS set up a Task Force on April 26, 2019.



One month after the fire, the CNRS and the Ministry of Culture, already linked by a cooperation agreement and joint laboratories, set up the Notre-Dame de Paris scientific project, appointed scientific coordinators, and structured the project into working groups. Contacts were quickly established with the project owner (DRAC Ile de France) and the chief architects of historic monuments in order to coordinate the diagnosis, securing and consolidation of the building with the removal, sorting and preservation of the remains, as well as the start of scientific projects.

This unprecedented multi- and interdisciplinary scientific project had two complementary objectives, "Science for Notre-Dame" and "Notre-Dame for Science," to quote Pascal Prunet, one of the chief architects of historic monuments involved in the restoration project. Lead pollution, the Covid pandemic, and above all, the time constraints imposed on the project owner and restoration project manager to restore the cathedral within five years are all crisis situations that academic scientists rarely face. In addition to the often-mentioned conflicts between short-term restoration projects and long-term scientific projects, there was also the time needed to adapt logistically to the crises and to understand the roles, missions, and skills of the actors involved in both projects in order to create a fruitful modus vivendi for cooperation.

The aim of this study is therefore not only to assess the scientific project in terms of its initial ambitions, but above all to analyze the impact of this unprecedented cooperation between science and restoration. On the one hand, it explores how this collaboration has impacted scientists, restoration professionals, and citizens in their practices and understanding of heritage and science. On the other hand, it examines what has made it possible to establish or bring together convergences of interest which, if encouraged, will have further effects on all these actors and on society.

The aim is therefore to analyze the impact of this unprecedented cooperation between science and restoration.

INITIAL EXTERNAL CONTEXT

INPUT and contributions from the CNRS and its partners

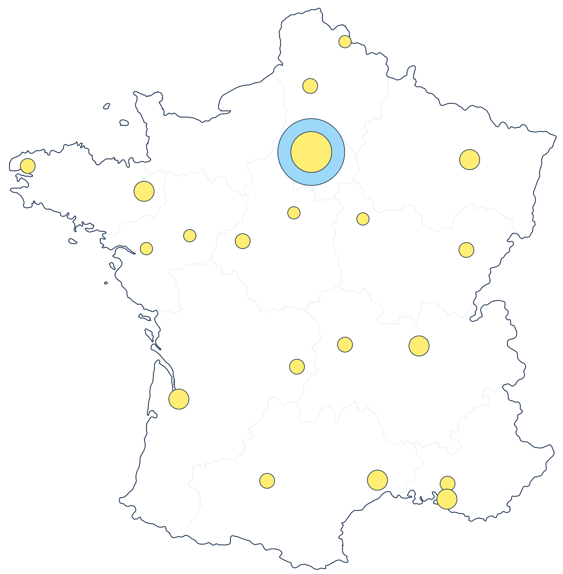
STRUCTURING OF THE SCIENTIFIC PROJECT

The scientific project was coordinated by **Philippe Dillmann and Martine Regert,** who were appointed to this task by the CEO of the CNRS, and **Aline Magnien and Pascal Liévaux** for the Ministry of Culture. On May 14, 2019, one month after the fire, the Ministry of Culture and the CNRS (represented by the Mission aux actions Transverses or MITI) decided to organize eight working groups: Wood and Framework, Metal, Stone, Glass and Stained Glass, Structure, Digital Data Ecosystem, Acoustics, Emotions and Mobilization. The ninth working group, Monumental Decorations, was created later. From the very beginning of the scientific project, it became clear that there was an urgent need to combine disciplines and expertise within each working group, with an awareness of the cross-disciplinary nature of digital technology.

These working groups, which were partly based on pre-existing collaborations and networks, brought together all the forces and skills in Heritage Sciences that wished to participate, i.e., approximately 180 research staff from all disciplines (including 20% CNRS agents). The scientists came from around 80 laboratories or organizations (including 50 affiliated with the CNRS) located throughout France but also from abroad, under the supervision of a wide variety of institutions: research organizations, universities, and the Ministry of Culture for the main ones (see Appendix 2).

INITIATION AND FUNDING OF THE SCIENTIFIC PROJECT

While MITI and then the Ministry of Culture quickly made funds available for the scientific project (€350,000 and €60,000 in 2020) to initiate scientific projects and cover organizational and digital aspects, scientists worked hard throughout the project to obtain regional, national (CNRS, ANR, Fondation des Sciences pour le Patrimoine, etc.), European (ERC, JPI Cultural Heritage) funds and also through agreements with the public institution responsible for the restoration of Notre-Dame (EP-RNDP). As a result, they have succeeded in raising nearly €8.5 million (some projects are still ongoing), which has enabled them to fund more than 20 PhDs. With an estimated 80 FTE scientists involved in the project, the project will have mobilized approximately €40 million in payroll costs (or approximately €78 million in total surrounded payroll costs).



Distribution of scientists across the country

Number of scientist involved per city

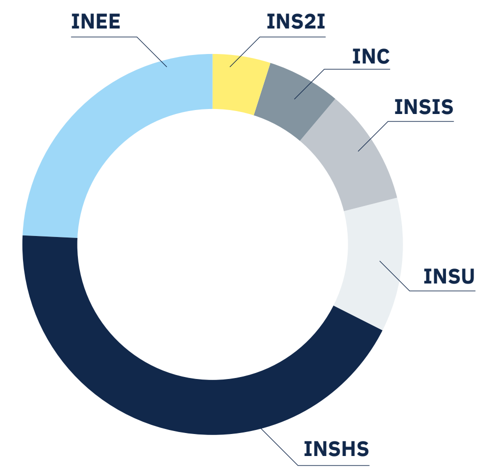
70
60
40
20

Number of scientists involved in the Ile-de-France Region (60)

LEGAL FRAMEWORK

In order to facilitate scientific cooperation, the MITI's cross-disciplinary "Notre-Dame project" initiative was incorporated into the 2020 amendment to the framework agreement between the CNRS and the Ministry of Culture. Specific agreements were implemented for the collection and use of digital data (charters). Subsequently, R&D agreements between the Structure Working Group and the EP-RNDP were established to provide a legal framework that derogates from public procurement codes and is adapted to research laboratories and, where applicable, to the transfer structures attached to these laboratories, which cannot assume legal responsibility for the results obtained.

List of CNRS institutes involved in the research



PROJECT MANAGEMENT, COORDINATION WITH THE RESTORATION PROJECT, ACCESS TO THE REMAINS

The scientific project was managed and coordinated through regular meetings between the working group leaders and the scientific project coordinators (approximately every two months, with more frequent meetings at the start of the project) and working sessions of varying formats within each working group. For example, the Stone WG organized annual meetings combined with visits and working sessions at other cathedrals (Laon, Sens, and Bourges).

But it was also necessary to coordinate the scientific project and the restoration project, both in terms of logistics and scientific issues. During the first year, monthly meetings with the restoration project manager, the project owner, and the DRAC ensured coordination between the scientific project and the consolidation, collection, and sorting of archaeological remains (carried out by the DRAC and the LRMH).

Although the EP-RNPD seemed uninterested in scientific issues at the start of the project, the organization of an initial symposium on the scientific project at the INHA in October 2020, attended by the CEO of the CNRS, the Minister of Culture, the Minister of Higher Education and Research, and General Georgelin (president of the EP-RNPD, who attended all the sessions), convinced all stakeholders of the relevance and value of combining a scientific project with the restoration project. Regular coordination meetings with the EP-RNPD and the project manager took place throughout the project; it should be noted that several members of the scientific project, including one of the coordinators, P. Dillmann, are members of the EP's Scientific Council..

In addition to the consolidation of the cathedral, heavy lead pollution caused by the fire delayed the intervention of scientists on the site: training on the risks of lead had to be organized and protective equipment procured. Some scientists (particularly those from the Metal and Acoustics working groups) were nevertheless able to access the site quickly, and a few participated in sorting through the remains, while the Digital working group was immediately mobilized to provide available digital data on the cathedral and a comparison of its condition before and after the fire.

However, most scientists were only able to access the cathedral from December 2019, shortly before the restoration work was severely disrupted by the Covid crisis, until June 2020. Finally, scientists' access to the archaeological remains was facilitated by the development of a storage facility in the Paris region, set up in 2021 and funded by the EP-RNDP.

During the restoration phase, scientists were able to take advantage of the site's facilities (scaffolding), which enabled them to make high-quality observations and measurements, but they had to avoid disrupting the work of the restoration companies. Some complained that access was too limited in terms of time or restricted to periods when the companies were not working, which probably hampered fruitful interaction between scientists and companies.

Although the fire occurred on April 15, 2019, the scientific project actually began decades earlier with the production of knowledge by stakeholders in each the relevant fields.

PREVIOUS WORK

The exemplary mobilization of scientists following the Notre-Dame fire was driven not only by the strong emotions aroused by this tragedy, felt by scientists as well as by French society and the international community, but also by the desire to put their expertise at the service of the restoration of the cathedral and its works of art. In fact, many of the scientists working on the project decided to put their current projects, and even their scientific ambitions, on hold in order to devote themselves full-time to the needs of the project.

Although the fire took place on April 15, 2019, the scientific project actually began years, even decades earlier, with the production by the participants of knowledge in each of the relevant fields that could be mobilized, either to answer urgent questions related to the restoration of Notre-Dame, to anticipate the needs of future restoration projects, or, in the longer term, to produce a body of data whose use by third parties is not yet foreseeable.

The main outputs and areas of expertise (non-exhaustive) of the various working groups on which the scientific project was based are listed below.

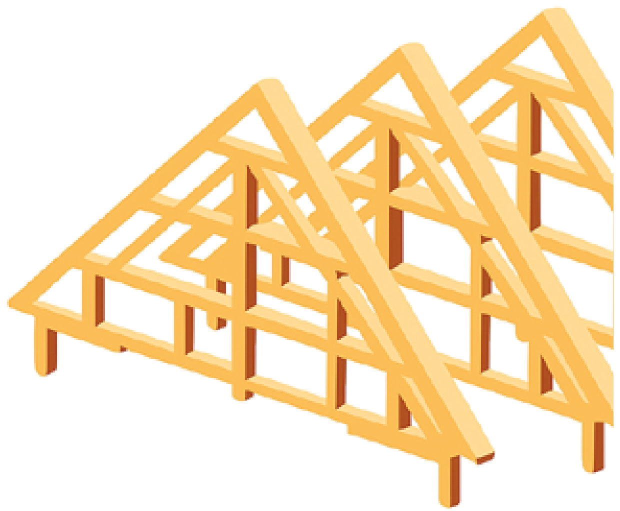
INPUT AND CONTRIBUTIONS FROM THE CNRS AND ITS PARTNERS

Wood WG (see additional references in the appendix)

1 Wood core sampling at Notre-Dame by Georges-Noël Lambert's team from the Chrono-Environment Laboratory in the 1990s (DEA V. Chevrier). The dendrochronological data was made available to the Wood Working Group by GN Lambert.
The archives, stored at the Chrono-Environment Laboratory, were also made accessible thanks to O. Girardclos.

2 The expertise of JY Hunot, a structural archaeologist at the Maine-et-Loire Department, and associated with the UMR CReAAH, who has specialized for 25 years in the archaeology of medieval and modern buildings, and whose research has led him to explore in depth the use of wood in construction, particularly the evolution of roof structures and roofing materials. JY Hunot is one of the authors of the book "Angers, La Grâce d'une cathédrale" (Angers, The Grace of a Cathedral), published by Place des Victoires.

3 The research conducted over the past 30 years by JL Dupouey and his team (UMR SILVA INRAE) in dendroecology, historical ecology, forest ecophysiology, silviculture, etc.



4 Research on charred wood by the BioArch laboratory (formerly AASPE), methodological developments, and the creation of an interdisciplinary group capable of studying charred wood from anatomical, chemical, and isotopic perspectives.

5 The work of the LSCE laboratory in dendroclimatology (V. Daux) and radiocarbon dating (C Hatté).

6 The GdR Sciences du Bois (Wood Sciences), of which some members of the WG were members, made it possible to broaden the scope of expertise to include wood mechanics in particular, and work on the behavior of freshly cut timber. Finally, the WG was able to take advantage of all the detailed surveys of the framework carried out by Fromont and Trentesaux in 2016.

Metal WG

No data had been produced on Notre-Dame, but the WG had more than 20 years of experience working on various topics related to metals in construction and on dozens of buildings (for example, for review: "Iron and lead in monumental construction in the Middle Ages, from the study of written sources to the analysis of materials. A review of 20 years of research and perspectives," Maxime L'Héritier, Ædificare, International Journal of Construction History 2019).

1 Archaeological and historical study of the uses of iron and lead in masonry.

2 Metallographic studies and mechanical testing (metal quality and shaping).

3 Studies on iron corrosion.

4 Dating of archaeological iron (since around 2015).

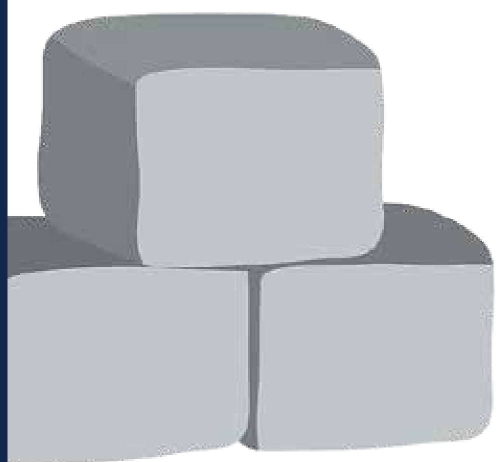
5 Provenance studies on archaeological iron using chemical analysis (since around 2010).

6 Chemical studies on the composition of lead weights (since 2010).

7 Isotopic tracing of lead (historical and pollution studies) (for over 20 years for pollution and tracing, but not yet applied to a monument).

Stone WG

1. Research on Gothic architecture produced by the scientific community in medieval art history (e.g., A. Ybert's thesis on Gothic vaults in Ile-de-France and Picardy, 2014).
2. Research on the materials used in Notre-Dame de Paris during previous restoration projects (1980s, LRMH lithotheque, work by L. Leroux) and on building stone in Paris and the Ile-de-France region, from Antiquity to the modern era (work by A. Blanc, M. Viré, JP Gély).
3. Research on the physical and chemical composition and mechanical behavior of ancient mortars (work by JM Mechling).
4. Expertise in building archaeology and construction archaeology, essential for carrying out authenticity assessments (= stone-by-stone study of elevations to identify parts restored at different times and parts that have not been restored).

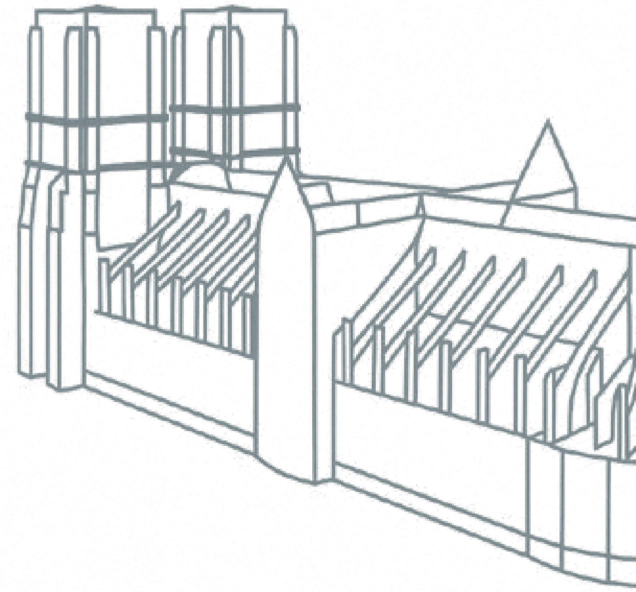


Glass and Stained Glass WG

1. As part of his expertise mission within the LRMH, C. Loisel studied the well-being condition of the upper windows of Notre-Dame in 2014 in order to draw up the specifications for future restoration work planned by Philippe Villeneuve, architect of historic monuments.
2. Historians have revisited the works of Corpus Vitrearum (begun in 1953), an inventory of stained glass windows, indicating the authenticity of the rose windows (https://notre-dame-de-paris.culture.gouv.fr/fr/les-vitraux-du-moyen-age; https://notre-dame-de-paris.culture.gouv.fr/fr/les-vitraux-du-xixe-siecle; https://notre-dame-de-paris.culture.gouv.fr/fr/les-vitraux-du-xxe-siecle)

Monumental Decor WG

1. Studies on the restoration of the western portals of Notre-Dame (special issue of the journal Monumental in 2000).
2. Participation of several members of the working group in the collective work published on the occasion of the 850th anniversary of Notre-Dame ("Notre-Dame de Paris," Strasbourg, Nuée bleue, 2012).
3. Comprehensive work published in 2013 (D. Sandron, A. Tallon, "Notre-Dame de Paris. Neuf siècles d'histoire," Paris, Parigramme, 2013, reprinted in 2019; English edition 2020) using the first scanner surveys of Notre-Dame carried out by Andrew Tallon.



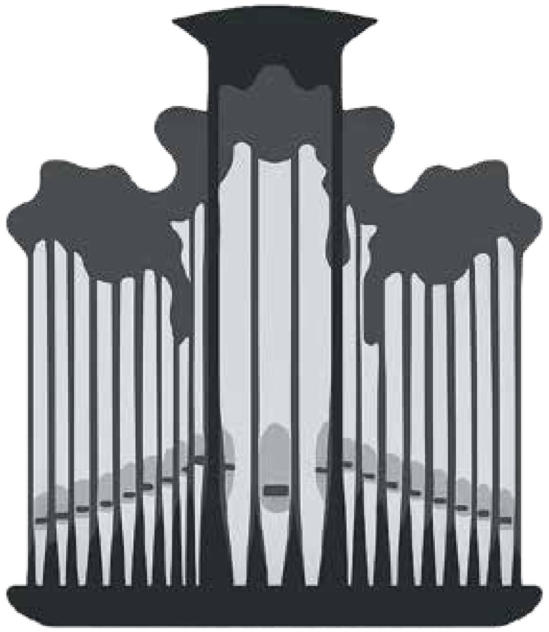
Structure WG (see additional references in the appendix)

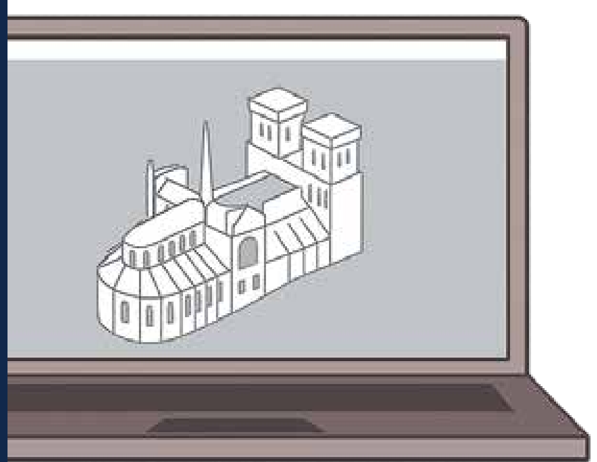
1. Work since 2010 on the mechanical behavior of stone masonry structures and its modeling.
2. Diagnosis of ancient masonry structures.
3. Effect of fires on masonry structures (since 2017).
4. Studies on mortars and adhesion between stone and mortar (2019).

Digital Data WG

1 L. De Luca participated in a working group set up by the Ministry of Culture to define guidelines for the 3D digitization of French monuments as part of the National Digitization Plan. This involvement enabled the WG to quickly identify the holders of 3D data on the condition of Notre-Dame before the fire and to assess its relevance in terms of restoration issues (technical specifications, degree of reusability).

2 Less than a year before the fire, the WG (MAP laboratory) had finalized the prototype of Aïoli, a web platform dedicated to 3D annotation for the collaborative documentation of heritage buildings. This tool proved to be central to the collection, spatialization, and interconnection of data produced by scientists and professionals working on the Notre-Dame site.





Acoustics WG (see additional references in the appendix)

1 Expertise in soundscapes developed since 2015: mastery of the entire production chain, from researching information in sources to its immersive dissemination, including recording and post-production.

2 Expertise in sound heritage developed since 2020.

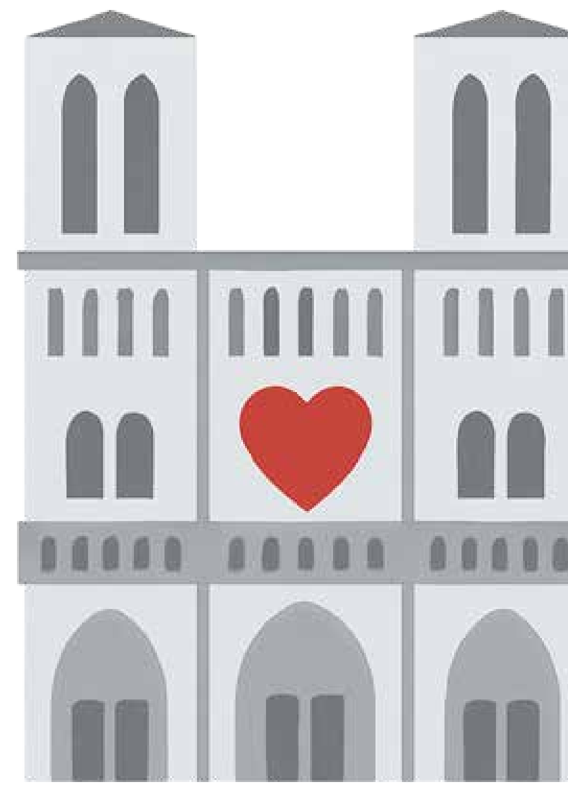
3 Expertise in acoustics, development of acoustic models for virtual reality audio, including at Notre-Dame since 2010.

Emotions / Mobilizations WG (EMOBI)

1 The anthropology of heritage: this strand of anthropological research was initiated by D. Fabre with the creation of Lahic (Laboratory of Anthropology and History of the Institution of Culture) in 2001. He is the founder of the WG, which he has enriched with his major research themes, such as the links between historical and material heritage and intangible heritage.

2 Heritage emotions: In the late 2000s, many members of the working group were part of the research group launched by D. Fabre on heritage emotions (see the collective work "Emotions Patrimoniales" published in 2013 by Éditions de la Maison des sciences de l'homme, as well as the Carnets du Lahic on the fire at the Palace of Lunéville (2010), the park of the Palace of Versailles after the storm of 1999 (2013) and the mobilization against the Borie dam (2010).

3 S. Sagnes launched a field study in the late 2010s on cultural mediation at Notre-Dame de Paris, focusing in particular on the guided tours provided by volunteers from the Communauté d'accueil (Host Community) at artistic sites, showing that, in its own way, guided tours contribute to the production of a heritage that is increasingly consubstantial with its mediation ("D'une quête l'autre : la visite de Notre-Dame," Les patrimoines en recherche(s) d'avenir, edited by E. Anheim, AJ Etter, G. Glasson-Deschaumes, P. Liévaux, Presses universitaires de Paris Ouest, Paris, 2019, pp. 109-120).



INPUT AND CONTRIBUTIONS FROM THE CNRS AND ITS PARTNERS

RESEARCH outputs

THE SCIENTIFIC PROJECT HAD TWO MAIN OBJECTIVES:

1. **SCIENCE FOR NOTRE-DAME:** to put the knowledge available in heritage sciences at the service of the restoration of Notre-Dame;

2. **NOTRE-DAME FOR SCIENCE:** to take advantage of privileged access to Notre-Dame to renew the body of knowledge on the cathedral, Gothic architecture, and the ancestral skills of its builders, but also to analyze an unprecedented anthropological situation with divisive heritage emotions, observable and studyable thanks to the unusual scale of the reactions and testimonies it elicited.

As mentioned above, the time constraints imposed on the restoration project, combined with lead pollution and the COVID crisis, greatly restricted access to the site and the availability of restoration teams for scientific work. As a result, some projects were completed too late for the scientific conclusions or recommendations to be taken into account in the restoration decisions, but they will be able to inform the thinking behind other restoration projects, at Notre-Dame or other historic monuments. Moreover, some working groups focused on elements (monumental decorations, stained glass windows) that were not or not heavily damaged by the fire.

WE WILL THEREFORE DISTINGUISH HERE BETWEEN:

- **SCIENTIFIC WORK** that supported the restoration project,
- **WORK THAT WILL BE USED FOR OTHER PROJECTS,**
- **AND WORK AIMED AT OTHER AUDIENCES,** such as the City of Paris, visitors, craftsmen, etc.

We have included in Appendix 3 the work aimed at renewing knowledge without any predictable short-term use (i.e., not related to any impact other than scientific at this stage). All the projects described have led to countless publications and other scientific outputs that we will not cite here.

SCIENTIFIC WORK
THAT SUPPORTED THE RESTORATION

DIGITAL SURVEYS BEFORE AND AFTER THE FIRE

The Digital Data Working Group, already involved in plans to digitize cultural heritage, was mobilized in the summer of 2019 by the restoration project manager (architects in chief) to help compare the condition of the cathedral before and after the fire. The first step was to retrieve existing digital data, in particular those obtained by Andrew Tallon, who died a few months before the fire, as well as sets of photographs showing the state of the cathedral before the fire. In order to establish the post-fire condition, it was necessary to acquire three-dimensional data (using laser scanning, photogrammetry, and drones) in collaboration with rope access technicians and the companies present.

The working group very quickly put the Aïoli platform into service to centralize and annotate the site data, in order to integrate the phases before and after the fire, but also to ensure partial monitoring of the restoration work. It should be noted that around a hundred people involved in the scientific and restoration work had access to this data (several states of the building represented in 3D) via a web viewer developed as part of the project. Remote access to this data proved crucial during periods of lockdown (COVID-19). The working group was thus able to compile spatialized documentation of the roof structures, vaults, and extrados of the vaults, both before and after the fire.

This study provided a virtual reconstruction of the roof structures before the fire at the architectural detail level, as well as the state of the deformations suffered by the vaults as a result of the fire. This enabled architects, engineering firms, and the Structure WG to study aspects relating to post-fire structural behavior.

In addition, the working group, in cooperation with other restoration project management and scientific site stakeholders, digitally reconstructed the nave's double arch and compression ring based on the digitization and analysis of the recovered voussoirs and fragments.

The scientific project was able to compile spatialized documentation of the framework, vaults, and extrados of the vaults, before and after the fire.

POST-FIRE DIAGNOSIS

Following the initial diagnostics carried out by the LRMH on the side walls at the end of April 2019 to check their solidity, several working groups were called upon to assist the restoration project management and engineering firms in establishing a post-fire diagnosis of the cathedral. In particular, at the request of the restoration project manager and in consultation with the engineering firms, the Structure Working Group set about assessing the post-fire mechanical behavior of the vaults of Notre-Dame (nave, choir, and transept), based on the initial state of equilibrium before the fire. This study was based on an original methodology known as the operating point method, which is based on a separate estimate of the behavior of the vaults and their supports, and contributed to the estimation of the equilibrium of the vaults and the post-fire thrust reserves. In addition, in order to improve the reliability of the simulated mechanical responses of the structure, different mechanical models were implemented simultaneously and compared.

Several additional studies were carried out:

- **the post-fire behavior** of the apse vaults, taking into account the interactions between the side vaults and the side walls;
- **thermal expansion** during the fire, and the impact of the water used to extinguish the fire;
- **the interactions** between the framework and the masonry;
- **and the stability** of a reinforced bay of the choir under the effect of wind.

During the fire, the stained-glass windows were protected in their entirety by the action of the firefighters and the resistance of the vault. However, an additional layer of atmospheric particles was deposited on the surface of the panels. The primary challenge was therefore to safely remove this lead-rich deposit for the restorers while preserving the stained-glass windows. It was therefore essential to characterize the surface deposits on the stained-glass windows in order to optimize the treatment methods for their restoration and to draw conclusions regarding the optimization of emergency protocols in the event of such a disaster. In this regard, the fire at the Cathedral of Saint Peter and Saint Paul in Nantes, during which the stained-glass windows were severely damaged, fueled the discussion.

MATERIALS FOR RESTORATION

One concern for the architects was to what extent certain materials from the cathedral, in particular the stones from the vaults and the iron clamps, could be reused in the restoration. The Stone and Metal Working Groups were called upon to rebuild the nave's transverse arch and test the reusability of the stones it was made of, and to analyze the quality of the iron after the fire. In the first case, it turned out that the original stones could not be reused; in the second, despite the good condition of the materials, the project manager opted for replacement.

THE BUILDING MATERIALS WERE ANALYZED TO SUPPLEMENT KNOWLEDGE ABOUT THE CATHEDRAL AND INFORM THE ARCHITECTS' DECISIONS:

- **PETROGRAPHIC CHARACTERIZATION,**
- **CHARACTERIZATION OF THE PROPERTIES** of the stone with a study of the stones suitable for rebuilding the vaults,
- **AND CHARACTERIZATION OF THE MORTARS.**

This enabled a physical and chemical study of the mortars used in Notre-Dame to be carried out, allowing the formulation of the mixtures to be reconstructed so that the project manager could use mortars with the same characteristics as those originally used.

While scientific data clearly established that young, green oak trees were originally used for the nave's framework, the Wood Working Group was able to provide the restoration project managers, project owners and engineering firms with information on the use and on the strength of freshly cut timber compared to dry wood, as well as dating the felling of the wood for the spire and comparing this date with Viollet-le-Duc's diary.

The structure working group then assisted the engineering firms with the structural aspects related to the use of freshly cut timber, in particular the dimensional variations of structural elements due to the drying of the wood. It should be noted that the carpenters, and in particular the association Charpentiers sans frontières (founded by François Calame, ethnologist at the Ministry of Culture), convinced the restoration project managers and contractors of their ability to rebuild the framework of the nave and choir identically, using squared timber. Finally, the structure working group provided scientific support to the restoration project owner during the design, execution, and construction phases by conducting scientific analysis of the design and construction specifications.

LEAD ALTERATIONS AND POLLUTION TRACING

The Metal Working Group was called upon very quickly after the fire by the City of Paris and the ARS (Regional Health Agency) to assess the impact of the lead pollution caused by the fire. The work carried out made it possible to establish the isotopic signature of the lead in Notre-Dame, which differs from the signature of "Parisian lead." Comparisons of pollution levels before and after the fire were made possible thanks to collaboration with the City of Paris in the year preceding the fire on the contamination of Parisian soil.

Numerous samples taken, particularly in response to complaints from local residents and associations, showed that while the square in front of Notre-Dame and the construction site were heavily contaminated, most of the pollution was carried away by the plume of smoke. The air pollution measured between April and November 2019 by the central laboratory of the police prefecture never exceeded the WHO guideline value and returned to pre-fire levels by July. Soil pollution, particularly in school playgrounds, also did not show the isotopic signature of lead from Notre-Dame.

On the other hand, blood lead level measurement campaigns detected new contaminated sites (unrelated to the fire), particularly in historic Parisian housing that still had white lead paint. These results led to very close monitoring of lead contamination by the City of Paris.

In addition, lead leaching studies made it possible to quantify the lead content released by roofing materials into rainwater and thus to design solutions to limit pollution. The interaction of molten lead with the metal, glass, or stone that makes up the building has led to the formation of lead compounds of various colors and morphologies, the nature and composition of which have been identified in order to better adapt the building's decontamination processes.

Acoustic measurements were taken on site to characterize the acoustics of the cathedral in its condition after the fire and in its condition after restoration.

ACOUSTIC STUDIES

Acoustic measurements were taken on site (from May-June 2019) to characterize the acoustics of the cathedral in its post-fire state and in its post-restoration state, in order to inform certain restoration choices (e.g., interactions with the organ). Although acoustic issues were not directly considered in the cleaning of the great organ, the Acoustics Working Group, at the request of the architects in chief and the EP-RNDP, provided a report to inform the technical choices concerning the choir organ following proposals from the pre-selected organ builders.

CONSTRUCTION OF EXCEPTIONALITY AND REGISTERS OF SACREDNESS

Finally, the EMOBI working group analyzed how and through what symbolic and/or technical operations the new materials that were brought into Notre-Dame for its reconstruction or restoration were, in a way, metabolized by the monument and integrated into its exceptional nature, with a focus on the use of traditional know-how and how it strengthened the link between the current construction site and the history of the building. At the same time, the working group sought to decipher the different registers of sacredness (religious, heritage, experiential, etc.) that fuel this exceptional nature and the way in which they have been hybridized in the context of the construction site: debris from the fire considered as quasi-relics, blessings of the logs intended for the new framework, transformation of the spire's cockerel into a memorial object incorporating both the same relics as its predecessor and the list of craftsmen who worked on the project.

The scientific project analyzed traditional know-how and how they have reinforced the link between the current project and the history of the building.

SCIENTIFIC WORK THAT CAN BE APPLIED **TO OTHER RESTORATION PROJECTS, INCLUDING NOTRE-DAME**

DIGITAL CATHEDRAL

The aim of this work was to create a digital ecosystem around a heritage object to support the scientific study and restoration of the cathedral, gradually integrating data, information, and knowledge from all those involved in the project around four complementary aspects: the collection and integration of existing digital data, the production of new data, its sharing and long-term archiving, its structuring and semantic enrichment. To date, this system has enabled the production of a unique corpus of tens of thousands of annotations, spatialized, semantized, linked to in situ observations, diagnoses, analysis results, and field data. In particular, it was necessary to define the strategy for digitizing the remains, the approaches to indexing and categorizing the data, and, based on all the collective data from the scientific project categorized and spatialized in 3D using the Aïoli platform, to explore the challenges of analysis and correlation using artificial intelligence. This corpus constitutes a structured record of the study protocols, knowledge, and scientific perspectives on the cathedral, and provides a unique reference base for long-term cross-analysis.

The ambition was to create a digital ecosystem around a heritage object to support the scientific study and restoration of the cathedral.

The digital cathedral has thus integrated data collected from cultural institutions, research laboratories, and companies (200,000 photographs before/after the fire and during restoration, 5,000 3D laser point clouds, more than 300 technical drawings, 5,000 documentary sources on the history of the cathedral), to which has been added all the data from the scientific project (material analyses, acoustic acquisitions, mechanical and acoustic simulations, technical studies, press and web resources, interviews, video documentaries, citizen surveys, etc.). ■■■

■■■ By integrating data from various fields (archaeology, mechanics, materials science, acoustics, anthropology, etc.) into a single digital ecosystem, this interdisciplinary approach promotes the emergence of new tools for analyzing, sharing, and exploiting information by scientists, restoration professionals, and even the general public. Several of the software tools developed as part of this project, particularly those related to annotation, spatial visualization, and semantic analysis, have been designed as reusable building blocks that can be adapted to other heritage collections. A charter has been established by the CNRS and the Ministry of Culture for the storage and use of data, which will make it freely available in accordance with the provisions of the Etalab 2.0 license, starting in 2025. The decision to distribute this data under an open license reinforces the collaborative nature of this initiative, providing a model that can be directly applied to other heritage studies and projects.

This is therefore a unique socio-technical system that can be developed for other monuments. It not only enables archiving, but also provides an evolving representation of the physical object and a progressive structuring of the knowledge associated with it.

POST-FIRE STRUCTURAL ASSESSMENT OF HISTORIC MONUMENTS

The Structure Working Group used nonlinear mechanical concepts to characterize the post-fire safety of built heritage, evaluating the thermomechanical properties of the materials used in masonry (limestone and lime mortar joints). The approach was based on hybrid modeling combining the interaction between blocks (frictional cohesive zone model) and the consideration of quasi-brittle damage to deformable blocks. This method was ultimately calibrated and validated with data from Notre-Dame in order to refine the thermomechanical modeling. This work, some of whose results arrived too late to be used in the restoration project, will be very useful for subsequent phases of the Notre-Dame project and for other restoration projects. The working group now has well-adapted tools that enable it to quickly perform preliminary analyses and produce more detailed models of the structures.

The scientific project now has well-suited tools that enable both to quickly perform preliminary analyses and to produce more detailed models of structures.

Work has focused on the morphology and age of the wood for an identical reconstruction.

CHARACTERIZATION OF WOOD AND FRAMEWORK FOR IDENTICAL RECONSTRUCTION

Analyses were carried out on the mechanical defects in the original wooden framework in order to correct them in the new framework by proposing appropriate construction measures. Detailed mechanical modeling, capable of accounting for the short- and long-term mechanical behavior of the framework, was thus carried out based on physical and mechanical knowledge of the wood used and medieval construction methods. A comparison between this modeling and a 1:1 scale replica of a frame module made it possible to prioritize the mechanical behaviors responsible for the actual flexibility observed in this frame.

Other projects have contributed to a better understanding of the history of the construction of the roof structure, its repairs, the technological innovations implemented, and certain assemblies. Finally, work has focused on the morphology and age of the wood for an identical reconstruction, including the species of oak used, the type of forestry, the geographical origin, the genetic lines, etc.

SOUND RECORDINGS OF THE TRADES AND THE CONSTRUCTION SITE: A TRAINING TOOL

Non-intrusive recordings made with the craftsmen during the construction site demonstrated the importance of listening in the proper implementation of craftsmanship and know-how, and the problems that can arise from construction site noise or the use of noise-canceling headphones. These recordings can be reused in other heritage projects for awareness-raising, documentation, and training purposes. Based on these recordings, training tools for craftsmen have been developed, based on virtual reproduction of movements and sounds (particularly in connection with the medieval construction site at Guédelon). These approaches can be transferred to other construction sites to raise craftsmen's awareness of sound issues.

MONUMENTAL DECORATION

The Monumental Decor Working Group focused on studying the monumental decor of Notre-Dame from various angles: 3D surveys, study of polychromy, comparative studies. 3D surveys (photogrammetric and laser scanning) were carried out on the western façade, the western portal, and inside the cathedral (bases, capitals, keystones), before being uploaded to the digital platform. A comprehensive study of the polychromy of the monumental decoration provided input for the international project "Notre-Dame in Color." Finally, comparative studies are being conducted, in particular to analyze the impact of the cathedral on the organization of the diocese of Paris, a key element in ecclesiastical geography, with dozens of churches to study, including Notre-Dame de Longpont-sur-Orge, as well as sculptures preserved in various museums around the world.

STAINED-GLASS

The Glass and Stained-Glass Working Group has developed projects to improve our understanding of the interaction between surface deposits and materials, focusing on two areas: the interaction between lead and materials, and the development of a new tool for the stratigraphic characterization of deposits (New-AGLAE). The aim was to gain a better understanding of the nature of the lead compounds produced during the fire and their interaction with the stained-glass elements, in order to develop appropriate decontamination protocols.

In 2021, the working group began an in-depth review of the authenticity of the stained-glass windows at Notre-Dame, particularly the three large rose windows (western, north transept, and south transept). The aim of this study was to map each panel precisely in order to distinguish the original medieval pieces from those added during successive restorations, particularly those carried out in the 19th century. At the same time, documentary research in historical archives has made it possible to trace past interventions and document restoration campaigns, particularly those carried out by Viollet-le-Duc. These investigations were supplemented by physical and chemical analyses (X-ray fluorescence spectrometry, ion beam analysis, optical spectroscopy, and Raman spectrometry) in order to accurately identify the composition of the glass and paints, as well as the techniques used during the different periods of production. This work thus constitutes an essential reference for the scientific and heritage management of Notre-Dame's stained-glass windows.

This work thus constitutes an essential reference for the scientific and heritage management of Notre-Dame's stained glass windows.

OTHER **PRODUCTIONS**

RECORDING THE SOUND AND VISUAL MEMORY OF THE CONSTRUCTION SITE, MATERIAL MEMORIES, COLLECTIVE OR INDIVIDUAL MEMORIES

Several working groups, notably the EMOBI WG and the Acoustics WG, have documented in detail the sound and visual memory of the Notre-Dame restoration project. Since 2020, visual ethnography conducted in the field has enabled the collection of approximately 600 hours of video recordings and around 100 hours of interviews with the various people involved. At the same time, sound recordings have captured the atmosphere and characteristic sounds of the site (the noise of tools, conversations between craftsmen, the general atmosphere of the site). These various recordings reveal not only the skills and technical gestures employed, but also the human interactions, the emotions felt, and the way in which each person experienced the progress of the project. They constitute a veritable collective memory of the project, recognized as such by those involved.

This data, collected from an ethnographic perspective, is currently being integrated into the digital ecosystem of the site developed by the Digital Working Group, where it will become a valuable resource for future interdisciplinary research. It enables the study of the collective and individual memory associated with the cathedral, whether in material form (objects, tools, physical traces) or immaterial form (memories, stories, shared emotions).

These recordings constitute a true collective memory of the construction site, recognized as such by its participants.

COMING TO NOTRE-DAME: EXPERIENCES AND PERCEPTIONS

The EMOBI working group conducted a large-scale survey to better understand how the public visits, perceives, and represents Notre-Dame. An online questionnaire was launched in 2020, gathering more than 2,500 responses. Particular attention was paid to visitors' practices around the cathedral and their expectations in terms of hospitality and mediation around the monument. The results obtained on practices were of direct interest to the City of Paris with a view to redeveloping the area around Notre-Dame, while the data on mediation is feeding into the Public Establishment's reflections on the future Notre-Dame museum. Finally, all the information gathered provides food for thought on tourism and cultural practices around the monument.

ACOUSTIC DIGITAL TWINS AT DIFFERENT PERIODS

The Acoustics Working Group has developed "acoustic digital twins" that can be used to virtually recreate the sound environment of the cathedral at different periods (medieval era, before/after the fire, etc.) or in different configurations. Based on sound recordings and enriched by documentary and archaeological research, particularly on historical furniture and textiles, the models accurately analyze the evolution of the monument's interior acoustics according to its architectural structure, its furnishings, and the presence of various decorative elements. For these simulations, sound sources were recorded in an anechoic chamber with singers' voices, a children's choir, speakers of classical French and Latin, and the sound of a large organ. Like the 3D digitization of the cathedral, the acoustic twins are vectors for cultural mediation and popularization, enabling immersive experiences (comparative virtual listening, virtual reality experiences).

Acoustic twins are vectors for cultural mediation and popularization, enabling immersive experiences.

RADIO DRAMA PODCAST, AUDIO GUIDE, AND VIRTUAL CONCERT

The Acoustics Working Group has contributed to several sound mediation projects, using recordings made on the construction site (soundscapes, testimonials, interviews) to recreate the sound experience of Notre-Dame in an immersive way. These productions combine scientific data, fictional stories, and authentic testimonials from those involved in the construction project. The podcast "À la Recherche de Notre-Dame" (In Search of Notre-Dame) is a radio drama available on Audible, inspired by Victor Hugo's imaginary reflections while writing his novel Notre-Dame de Paris. Designed as a sound exploration of the monument through the centuries, it uses recordings and acoustic simulations to recreate different historical atmospheres. In addition, the "WhispersND — Murmures du passé à Notre-Dame" app, available on smartphones, offers an immersive audio tour of the cathedral. Finally, an audio guide project for the interior of the cathedral is currently under consideration, aiming to offer visitors an enriched sound experience. These various productions seek to highlight the sensory dimension of the monument while taking into account its liturgical and cultural aspects, in order to reconcile the sacred identity of the place with a heritage experience accessible to the general public. Finally, the virtual concert "ArchéoConcert," in the form of a medium-length film, presents 11 musical pieces associated with Notre-Dame over a period of more than eight centuries, each recorded in a studio and reproduced in 3D audio with the acoustics appropriate to its era.

Coupled with documentary elements to place each scene in its musicological and/or historical context, and complemented by graphics featuring animated musicians, this film was screened in 2025 during UNESCO's Sound Week, then at the French Acoustics Congress, and will be available online free of charge from July 2025.

KNOWLEDGE sharing and intermediaries

The Notre-Dame project is unique in that it brought together scientists and restoration professionals (project owners, restoration project managers, engineering firms, restorers, contractors) in the same place at the same time.

As a result, the research was either conducted in response to a request from restoration professionals, co-produced with some of these professionals, or disseminated to interested parties in near real time. Everyone agrees that the Notre-Dame project will become a world reference in terms of restoration, including its scientific aspects, which will benefit future projects.

In addition, scientists have widely communicated their work through national and international symposiums, popular science conferences, and exhibitions.

They have also been in high demand by the media (regional and national print media, radio, TV, etc.), thus helping to open up new areas of interest.

The experience gained from the daily interaction between the worlds of science and heritage restoration, combined with intensive communication with all audiences, has enabled and will continue to enable the initiation of new aspects related to this cooperation. It also promotes the appropriation of knowledge gained from the scientific project by other actors, who will be able to exploit it and make it bear fruit.

RESTORATION PROJECT MANAGEMENT AND PROJECT SUPERVISION

In the context of the restoration of historic monuments belonging to the State, the Regional Directorates for Cultural Affairs (DRAC) are responsible for project management and are therefore tasked with overseeing, coordinating, and carrying out studies and operations contributing to conservation and restoration, under the supervision of the chief architects of historic monuments (ACMH). For National Monuments, the restoration project management is carried out by the Centre des Monuments Nationaux (CMN). In the case of the restoration of Notre-Dame Cathedral in Paris, the conservation and restoration work has been entrusted to the public institution EP-RNDP, created for this purpose by the decree of November 28, 2019. Each ACMH is normally assigned to a specific geographical area. Given the scale of the Notre-Dame de Paris project, which requires a wide range of skills, the project management was entrusted to Philippe Villeneuve, who was assisted by two other ACMHs, Rémi Fromont and Pascal Prunet.

In everyone's opinion, the Notre-Dame restoration project will become a globalbenchmark in terms of restoration, including its scientific aspects, which will benefit future projects.

Following the Notre-Dame scientific project, DRACs (or other partners) have already had the opportunity to call on members of the scientific project team to help with the restoration of various historic monuments. Among various examples, the Structure Working Group is involved in the structural assessment of the Bordeaux spire, and the MAP laboratory (Digital Working Group) has signed an agreement with the CMN for the integration of 3D digitization data sets for 25 monuments.

The success of the Notre-Dame scientific project has also led to the creation of a joint thematic network between the CNRS and the Ministry of Culture, called MAESTRO ("Understanding the challenges of major monuments: MAtEriaux, STRuctures, EnvirOnnements"). The Department of Research, Promotion, and Tangible and Intangible Cultural Heritage, the Sub-Directorate for Historic Monuments and Heritage Sites, and the DRACs are represented on the steering committee of this network.

This will enable the DRACs to benefit from the scientific support of those involved in the Notre-Dame scientific project, from the diagnostic phase through to the construction phase, in order to justify and even reinforce their decisions regarding restoration.

Finally, in addition to deepening their knowledge, ACMHs express the need for ongoing exchange and discussion with scientists on restoration projects , whether to better objectify their choices and decisions or to support the evolution of current restoration doctrines and methods. In addition, they would like to see a collective reflection on the evolution of standards (freshly cut timber, lead, etc.) based on rigorous scientific data that is convincing to third parties.

ENGINEERING FIRMS

The engineering firms called upon by restoration projects essentially have a dual role in the engineering and architecture of historic monuments: in a historic monument, a scientific structural approach and historical knowledge of buildings are inseparable. They are therefore the perfect interface between ACMH and scientists. Structural modeling, even when developed by expert scientists in the field, does not yet allow for accurate predictions of the behavior of old buildings. However, these theoretical models make it possible to question and deepen the analyses of engineering firms and architects on critical points. Furthermore, comparing them with the historical reality of monuments, whether in terms of construction techniques or the evolution of structures over time, allows them to be gradually refined and made increasingly relevant.

From the perspective of the engineering firms involved in the Notre-Dame project, this collaboration has therefore proved very rewarding for all parties and deserves to be continued in future projects requiring in-depth consideration of the structure of monuments.

RESTORATION COMPANIES

The companies in charge of the structural elements (masonry, framework) of historic monuments have knowledge and expertise that complements academic knowledge. They are therefore keen to establish more contacts and share ideas with scientists, whether to improve the training of professionals (for example, by using training tools based on virtual reproduction of movements and sounds) or to develop new approaches, including for new buildings. Scientists are thus sought after for their knowledge of freshly cut timber (see following paragraph).

STANDARDIZATION BODIES AND INSURERS

The quality standards that apply in the building industry are designed exclusively for new buildings and not for historic monuments. However, the restoration of historic monuments is governed by the International Charter for the Conservation and Restoration of Monuments and Sites, known as the Venice Charter (1964), a set of guidelines that provides an international framework for the preservation and restoration of ancient objects and buildings: "Restoration must mean conserving and revealing the aesthetic and historical values of the monument being restored, based on respect for the old substance and authentic documents." This charter was updated in 2000 in Krakow, adopting a more modernist approach. The restoration of historic buildings can now make use of modern materials and techniques, provided that they are rigorously tested, compared, and mastered before application, and then subject to ongoing monitoring. ■■■

■■■ The restoration of Notre-Dame was based on the principle of identical restoration, using the same materials and construction techniques where possible. Thus, the roof structure and spire were rebuilt using freshly cut timber (moisture content above 30%). However, the moisture content of wood used in the construction of houses and buildings (wood frames and roof structures) is specified in DTU 31.1 and 31.2 ("Unified Technical Documents"): it must be less than 18% on average and must not exceed 22% at any given time. Similarly, the repair of the lead roof contravenes European standards in this area.

Compliance with standards is THE condition for a building to be declared compliant and insurable. ACMH are therefore faced with conflicting requirements in a context where the liability of stakeholders, including companies, and their insurability are at stake. Architects and companies therefore want to be able to rely on robust and objective data and measurements, provided by scientists, to develop standards and convince insurers. This would make it possible to relax the restrictive and contradictory regulatory framework for historic monuments. Standardization bodies (CSTB, AFNOR) and insurers are therefore key intermediaries for the use of scientific data to adapt standards and develop new construction methods for heritage buildings. These developments could also benefit new buildings, particularly for economic and environmental reasons.

EXPERIMENTAL MEDIEVAL CONSTRUCTION SITES

The medieval construction site at Guédelon aims to build a "new" castle, dating from the first third of the 13th century and featuring Philippian architecture. An experimental archaeological site, advised by a scientific committee, this project, which began in 1995, has enabled the workers at Guédelon to rediscover, pass on, and perpetuate the skills of the builders. In addition to being a tool for popularization, with its 300,000 visitors per year, Guédelon is also a source of inspiration, reflection, practice, and exchange for scientists and all those involved in restoration. Many of those involved in the Notre-Dame project, including architects, craftsmen, and scientists, have benefited from exchanges, training, and experimentation at the Guédelon site, which in turn draws on the insights gained from the project.

More recently, another experimental project has been launched, the medieval site of Guyenne, whose ambition is to build an architectural complex ranging from Romanesque to Gothic using the techniques of the builders of the time and thus attempt to understand, through experimental archaeology, how the jewels of our architectural heritage, the cathedrals, were built. The symposiums of the Notre-Dame scientific project have enabled scientists to meet and collaborate with the medieval Guyenne project, whose scientific council is partly made up of members of the Notre-Dame scientific project.

MUSEUM PROJECT FOR NOTRE-DAME AND HERITAGE MEDIATION

A museum project for Notre-Dame, requested by the President of the Republic, is currently in the preliminary stages, under the responsibility of Charles Personnaz (director of the Institut National du Patrimoine) and Jonathan Truillet (EP-RNDP). Scientists have been involved in the planning of this museum from the outset. It would be the ideal setting to showcase and share the results of the scientific project with the public, but also to archive, in one place, all scientific output, regardless of its format (digital, visual, audio, graphic, etc.). In addition, the wealth of data collected, combined with advances in 3D annotation and artificial intelligence, paves the way for new heritage mediation practices. For example, immersive virtual reality experiences, developed in collaboration with Dassault Systèmes, allow the public to explore the history and architecture of the monument from a new angle. Acoustic twins also open up new possibilities for cultural mediation and popularization, enabling immersive experiences (comparative virtual listening, virtual reality experiences) where the public can rediscover the acoustics of Notre-Dame in different historical configurations.

A museum project would indeed an ideal showcase to highlight and share with the public the results of the scientific work.

EDUCATIONAL INSTITUTIONS

Apart from the impact of the Notre-Dame restoration project on the practices of the various parties currently involved in restoration work, the intertwining of scientific and restoration projects and the confrontation of different points of view has given rise to a reflection on the training of future professionals, whether they be scientists, architects, craftsmen, etc. The culture of fruitful dialogue between scientists (beyond those working in the laboratories of the Ministry of Culture) and restoration professionals, in the service of heritage restoration, must be integrated into various training programs in order to endure and grow. Internships in companies (including craftsmen and journeymen) for future heritage scientists to better understand the knowledge and expertise of companies and journeymen, but also the constraints of a restoration project, more involvement of scientists in the training of architects of historic monuments and in initial or continuing training in heritage professions (professional bachelor degrees, links to be established with the French group of historic monument restoration companies GMH or with CAPEB, etc.) are among the initiatives suggested by the various stakeholders.

CITY OF PARIS

The work of the metal working group on lead pollution before and after the Notre-Dame fire led to the City of Paris stepping up its monitoring of lead contamination, which it had already been doing for several decades. In September 2019, the City of Paris launched an action plan against lead pollution, in line with its Paris Health and Environment Plan. In particular, the City of Paris has launched investigations to detect the presence of lead in its establishments that welcome children (nurseries, preschools, and elementary schools). The City of Paris and the Île-de-France Regional Health Agency (ARS) are paying particular attention to the presence of lead in Paris's major historical monuments, in conjunction with the institutions involved in their conservation and restoration.

In addition, the City of Paris has been working with the EMOBI working group since the planning phase of the project to redevelop the area around Notre-Dame, which is scheduled to begin in 2025. The working group contributed to the urban, semiotic, and historical studies carried out on the site by means of a questionnaire designed to gather the memories of visitors and Parisians in order to better understand their expectations (see project presentation report and Paris Council deliberations, 2021 SG20).

MEDIA

It is impossible to count the number of times scientists have appeared in the national and international press, radio, and audiovisual media, as they have been so frequent throughout the project, demonstrating the interest of the media and the public not only in the restoration of Notre-Dame but also in the scientific project. For example, according to the Europress database, which lists 8,183 press titles, there have been 160 articles mentioning the scientific work since April 15, 2019. In addition to these individual requests, the scientists also designed a book for the general public, "Notre-Dame de Paris: la science à l'œuvre" (Notre-Dame de Paris: Science at Work), published by Éditions du Cherche Midi in 2022.

Above all, they were at the heart of a three-part documentary series produced by ZED (C. Le Goff) and broadcast on Arte, "Notre-Dame de Paris: le chantier du siècle" (Notre-Dame de Paris: the restoration site of the century), followed by a fourth installment, "Les trésors enfouis de Notre-Dame" (The buried treasures of Notre-Dame), focusing on the excavations carried out by INRAP and describing the discovery of the rood screen and lead coffins. Across all media (live broadcast, replay platform, YouTube), these documentaries have accumulated 17 million views, with the first broadcast of the triptych in 2023 and the fourth installment in 2024 even breaking audience records.

Their success was undoubtedly facilitated by a long-term filming process carried out in a climate of great trust between scientists, directors, and producers. The enthusiasm of viewers can be summed up as "*we are at the heart of the research, we understand*" (comments reported by the producer). It should also be noted that some sequences in Jean-Jacques Annaud's film "Notre-Dame brûle" used digital data provided by the digital working group. Finally, the scientific project and its participants took part in several exhibitions, including "Notre-Dame de Paris: from builders to restorers" at the Cité de l'Architecture et du Patrimoine, "Capital Image" at the Centre Pompidou, "Notre-Dame de Paris: au cœur du chantier" (Notre-Dame de Paris: at the heart of the project) under the forecourt of Notre-Dame, and the European Heritage Days. Each time, the exhibitions were a great success, demonstrating the French public's attachment to their heritage and to all those involved in its restoration and promotion.

The enthusiasm of the spectators can be summed up as «we are at the heart of the research, we understand.»

IMPACTS

Conceptually, the impact of research must always be considered in relation to a counterfactual, i.e., the effects compared to a scenario without the research.

As the analysis of the impacts of the Notre-Dame scientific project was carried out shortly after the end of the project, it is difficult to have an objective view of all the societal impacts. We will therefore distinguish between impacts that are already observable or proven, impacts that have been initiated or are expected, and impacts that we anticipate or hope will occur.

SCIENTIFIC **IMPACT**

STRUCTURING OF HERITAGE SCIENCES AND THE MAESTRO THEMATIC NETWORK (proven and expected impact)

Due to its scale, the project has strengthened the structuring of heritage sciences as a multidisciplinary field of research. The mobilization of nearly 200 researchers, the funding of more than 20 PhDs, the awarding of specific contracts at the national and European levels, and the collective organization of working groups combining the humanities, engineering, and experimental sciences have contributed to increased efficiency in this field. The work of the scientific project has led to numerous advances (new methodologies for analyzing materials and structures, capturing heritage emotion, deploying digital technology, etc.) that constitute a reference base for the structuring of heritage sciences, which is expected at the national level and hoped for at the international level thanks to the establishment of collaborations.

This structuring took concrete form with the creation of the MAESTRO Thematic Network in 2025, bringing together most of the scientific players in the field. Beyond purely scientific aspects, this network aims to facilitate researchers' access to heritage sites in France and to develop scientific intervention mechanisms adapted to the time constraints of restoration projects. This impact is currently being consolidated, with strong structuring potential and tangible consequences for the restoration professions, if the network actively develops sustainable collaborations with architects, engineering firms, craftsmen, and companies.

THE PIVOTAL ROLE OF DIGITAL TECHNOLOGY IN HERITAGE ANALYSIS (proven and expected impact)

The project also helped position the digital dimension as a cross-cutting component of heritage research, particularly through the development of a platform dedicated to the management, archiving, and visualization of documented 3D data. This platform is not limited to visualization: it enables the cross-exploration of multidimensional corpora, the spatial and temporal anchoring of observations, and the integration of structured semantic layers, thus facilitating unprecedented analyses at the scale of a building. This pivotal role is now recognized by the various stakeholders and could eventually become a standard for the analysis, documentation, and archiving of heritage data. Beyond this project, the interoperability of the tools and methods developed paves the way for their transposition to other heritage contexts, reinforcing the national and international scope of this approach.

STRENGTHENING OF COOPERATION BETWEEN THE CNRS AND THE MINISTRY OF CULTURE (proven impact) AND INTER-INSTITUTIONAL GOVERNANCE (proven and expected impact)

Finally, the project laid the foundations for strengthened inter-institutional governance between the CNRS and the Ministry of Culture, in conjunction with the various institutions involved in the restoration of Notre-Dame (EP-RNDP, DRAC, Ministry of Culture laboratories). This cooperation, which was quickly established after the fire, made it possible to test a logistical, scientific, and legal framework in a crisis context. Although it remains incomplete, with some difficulties identified concerning administrative delays, access to the site, and the distribution of responsibilities, its impact is nevertheless evident for the actors involved. It thus provides a basis for improving protocols for access and scientific intervention in the event of heritage disasters.

CULTURAL **IMPACT**

The experience of the Notre-Dame scientific project, combined with a restoration of such magnitude, is already setting an international reference for the scientific management of a heritage crisis, both for its impact on restoration and practices and for its impact on the public, amplifying everyone's interest in heritage.

As one of the architects interviewed said, "without the scientific project, the restoration of Notre-Dame would have taken place, but not in the same way."

HERITAGE RESTORATION

(expected impact)

According to all those involved, there will be a before and after Notre-Dame in terms of the restoration of historic monuments. This project has indeed initiated a change in restoration practices, which will need to be continued in the future, through an approach that better involves scientists, architects, engineering firms, restorers, and companies, from the diagnostic phase to the construction phase, in order to better respond to technical and economic challenges, as well as challenges related to global changes (including climate and environmental changes).

On the other hand, we must now capitalize on this unprecedented experience to engage in a collective reflection on the doctrines of heritage restoration, particularly on the concepts of the last known state, the reuse of materials, beauty and utility (a compromise between aesthetics, authenticity, and sustainability), the response to sustainable development objectives, and the appropriation of heritage by all. In short, we need to adapt the principles of heritage restoration to the challenges of the 21st century with a view to eventually revising the Krakow Charter.

The scientific project has given rise to new forms of storytelling and heritage design, combining individual emotions, collective memory, science and restoration, including the intertwining of ancestral know-how and technological innovations.

ACCESS FOR ALL TO HERITAGE CULTURE

(proven impact)

The scientific project at Notre-Dame has given rise to new forms of storytelling and heritage design, combining individual emotions, collective memory, science, and restoration, including the intertwining of ancestral know-how and technological innovations, and the central role of digital technology in the appropriation of heritage but also in archiving. While the restored cathedral and its remains are the subject of numerous cultural events, the collective human adventure that presided over the restoration of Notre-Dame, and for which the scientific project produced analytical, visual, and acoustic memorial materials, has itself become a subject of heritage. Thus, the scientific output of the restoration project has underpinned a wide range of communication initiatives that give a very large audience access to heritage culture, including exhibitions, documentaries, books, podcasts, immersive spatial and acoustic experiences, public lectures, and plans for a future museum dedicated to Notre-Dame. This enthusiasm for heritage and its restoration is also reflected in the success of experimental medieval construction sites, which are experimental grounds for medieval architecture, know-how, and scientific approaches accessible to all.

ENVIRONMENTAL **IMPACT**
(partly proven and partly expected)

The large-scale restoration of Notre-Dame has catalyzed reflection on more sustainable restoration practices, using materials that are not only appropriate for heritage constraints but also more environmentally friendly.

This involves reusing or using more environmentally friendly materials, setting up short supply chains and sustainable resource management, and taking into account the pollution caused by certain materials.

The restoration of the roof structure and spire using freshly cut timber, in line with original techniques, raises questions for the entire timber industry on a range of issues, such as the role of craftsmanship versus industry (freshly cut timber must be partly squared by hand), forest management in climate change conditions, and the measured use of local resources or reuse. While freshly cut timber offers an obvious ecological advantage, as no drying or treatment is required, it does require that forestry practices be adapted and, above all, anticipated.

More regular use of freshly cut timber in the restoration of historic monuments (or even new buildings) will require joint reflection by restorers, scientists specializing in wood and climate, the National Forestry Office, France Bois Forêt (the national interprofessional organization for the forestry and wood industry), and Charpentiers sans frontières, which has contributed greatly to reviving this expertise. Scientific studies clearly indicated that the reuse of stones from Notre-Dame was out of the question, as the stones from the collapsed vaults had been weakened by the fire that destroyed the roof structure. Fortunately, the joint efforts of the Stone working group and BRGM groups made it possible to precisely determine the characteristics of the stones used in Notre-Dame and to identify new quarries of the same type in the Oise and Aisne departments (the old Paris quarries having been closed) capable of meeting the needs of the Notre-Dame restoration, both in terms of quality and quantity (1,300 m^3 of stone were needed!).

OUTPUT

Short supply chains have thus been made possible, but this should not obscure the fact that the closure of many quarries in France (for both economic and ecological reasons) may, in the future, jeopardize this type of supply and force architects and restorers to import stone from much further afield. Here again, when considering materials for restoration, it is necessary to weigh up the heritage constraints of restoration against the sustainable management of resources.

The Metal Working Group has certainly made it possible to ensure the safe use of lead in roofing and to produce studies enabling rigorous monitoring of lead in Notre-Dame after the fire. However, this does not detract from the fact that lead is a proven pollutant and toxic substance. Moreover, the lead sheets for the roof were imported from Great Britain, where occupational health regulations are more flexible. Is it reasonable in the long term to disregard European regulations in order to comply strictly with the recommendations of the Venice/Krakow Charter? Here again, robust and objective scientific evidence and data should fuel a necessary debate, especially since, in addition to roofing, the art of stained glass cannot be practiced without lead. No one would understand if the stained-glass windows were bricked up because they could not be restored! What reasonable and sensible measures can be proposed?

The Notre-Dame project is therefore also a reference point in terms of the environmental impact of restoration and the risks that climate change and inadequate resource management pose to heritage restoration. These are all questions that scientists have helped to bring to light, scientists whose multidisciplinary and interdisciplinary skills will be required to objectify future debates and enable the adaptation of current doctrines and standards.

The Notre-Dame project is also a benchmark in terms of environmental impact of restoration and the risks that climate change and inadequate resource management pose to heritage restoration.

SOCIAL **IMPACT**

The Notre-Dame scientific project has helped to create a positive dynamic in terms of training and the attractiveness of heritage restoration professions.

The scale and complexity of the project have highlighted the value of strengthening cross-disciplinary training, bringing together researchers, field professionals, architects, contractors, and craftsmen to facilitate exchanges and mutual understanding between these different actors. Although such cross-disciplinary training has only been tried on a relatively limited scale during the project, the momentum that has been built could encourage its development in the future.

TRAINING SCIENTISTS IN HERITAGE SCIENCES
(proven and expected impact)

On a scientific level, the project has enabled more than 20 PhD students to be trained in various disciplines related to heritage sciences (art history, engineering, materials, digital technology, etc.). This impact on academic training is clear, with young researchers acquiring skills that can be applied to other heritage restoration projects, thereby strengthening the pool of experts in heritage sciences.

The project has also prompted reflection on the importance of bringing academic training for scientists closer to the operational aspects of heritage restoration. Concrete initiatives such as internships in companies (with craftsmen, journeymen, and engineering firms) are suggested to enable scientists to better understand the specific know-how and operational constraints of a project. While these training courses still need to be organized and implemented, the recommendations resulting from discussions during the project provide a solid basis for their future integration.

SCIENTISTS' INVOLVEMENT IN PROFESSIONAL TRAINING
(expected impact)

The scientists involved in the project have made occasional contributions to initial and continuing training courses in heritage professions (vocational degrees, apprenticeship training centers, vocational high schools, guilds). Those involved in the project suggested making these contributions a permanent feature, in particular by strengthening links with professional groups such as the French Association of Historic Monument Restoration Companies (GMH) and CAPEB. Discussions on the project site also highlighted the value of using innovative teaching tools, such as virtual reproductions of technical gestures or sounds, to improve the training of professionals.

In addition, roundtable discussions or thematic workshops for and with historic monument architects would be appreciated. More generally, architects, engineering firms, and the Institut National du Patrimoine (National Heritage Institute) highlighted the shortcomings of the training provided by the Ecole de Chaillot in scientific and engineering aspects. They insisted on the need to raise awareness among future ACMHs of these approaches, as well as the importance of identifying and mobilizing scientific expertise that could be useful for their projects.

ATTRACTIVENESS OF HERITAGE PROFESSIONS (expected and hoped-for impact)

The scientific project has indirectly contributed to promoting careers related to heritage restoration (carpenters, stonemasons, engineers specializing in masonry, etc.). By highlighting their technical nature, their complementarity with academic knowledge, and their cultural value, it has increased their visibility among the general public and younger generations. Some companies, particularly those working on structural elements (masonry, carpentry), have expressed a keen interest in sharing ideas with scientists in order to develop new approaches, including for new buildings, and to promote their professions to educational and professional bodies. Finally, presenting the experience of the Notre-Dame scientific project in academic training programs helps to increase the attractiveness of certain fields, such as masonry in civil engineering programs.

POLITICAL AND REGULATORY **IMPACT**

The Notre-Dame scientific project has clearly demonstrated the importance of taking scientific contributions into account when developing heritage and regulatory policies.

Through its scientific results, but also through the discussions it has sparked, the project is helping to fuel and enrich reflections on the evolution of conservation policies and standards applicable to historic monuments.

INFORM CONSERVATION POLICIES BY INCORPORATING PUBLIC PERCEPTION (expected impact)

The scientific project has shed new light on citizens' expectations and perceptions of heritage restoration, particularly through studies on the collective emotions and social mobilization triggered by the Notre-Dame fire. These analyses can thus feed into institutional discussions (Ministry of Culture, DRAC, public institution responsible for restoration) so that heritage conservation policies take greater account of how they are understood and received by different audiences. This dimension appears particularly relevant in guiding sensitive projects such as the rehabilitation of the area surrounding Notre-Dame, in its urban, cultural, and political dimensions, particularly in relation to the City of Paris.

The scientific project has provided a new insight into citizens' expectations and perceptions of heritage restoration.

CHANGES IN BUILDING STANDARDS RELATING TO THE USE OF FRESHLY CUT TIMBER (expected and hoped-for impact)

The restoration of Notre-Dame's roof structure and spire using freshly cut timber, in accordance with original techniques, has highlighted regulatory issues related to this material, which has been little used in monumental heritage over recent decades. This choice, validated by scientific studies carried out on the site, now calls into question existing technical, environmental, and regulatory standards and calls for these standards to be adapted to better take into account the technical specificities of freshly cut timber, particularly with regard to the durability of structures during the critical period of drying. Furthermore, this choice raises the essential question of the insurability of the structures, as current standards impose constraints that are difficult to reconcile with the specific characteristics of heritage buildings. Several institutional players (the National Forestry Office, France Bois Forêt, the Ministry of Culture), as well as insurers and standardization bodies, will need to be called upon to engage in this regulatory debate, which is expected to take place in the coming years. These developments, based on the scientific results of the Notre-Dame project, could also benefit new buildings in the long term.

The restoration of the roof structure and spire of Notre-Dame using green wood has highlighted normative issues related to this material, which has been little used in monumental heritage over the last few decades.

CHANGES IN STANDARDS FOR THE USE OF LEAD IN THE RESTORATION OF HISTORIC MONUMENTS (expected impact)

The use of lead on historic monuments, particularly in the emblematic case of Notre-Dame, has sparked significant debate on environmental and health standards. The scientific project has deepened our understanding of the impacts of lead in terms of pollution and public health, but has also revealed the need to clarify the regulations applicable to this material, particularly at the European level. These scientific findings should inform institutional discussions on the relevance and conditions of lead use in heritage restoration projects, which is an impact hoped for by several stakeholders in the project (DRAC, the public institution responsible for restoration, companies, and scientists involved).

ECONOMIC **IMPACT**

REVENUE FROM HERITAGE MEDIATION
(proven impact)

The Notre-Dame scientific project has given rise to a wide range of heritage mediation activities (exhibitions, documentaries, books, press articles, etc.) which have attracted a large number of readers, visitors, listeners, and viewers. For example, the documentary series "Notre-Dame de Paris: le chantier du siècle" (ZED production, broadcast on ARTE) has accumulated 17 million views. According to the Europress database, 160 press articles have mentioned the scientific project since April 15, 2019, to date, bearing in mind that this database contains 8,183 referenced press titles. These productions have therefore generated revenue for the museums, producers, publishers, and media outlets involved, although the exact amount remains difficult to estimate.

Concerted action by professionals, architects, engineers, and scientists will undoubtedly help convince others of the merits of the freshly cut timber industry and thus support its future development.

THE FRESHLY CUT TIMBER SECTOR FOR CONSTRUCTION (expected impact)

The restoration of Notre-Dame de Paris has highlighted freshly cut timber framing techniques that had virtually disappeared in the 20th century. In a context of sustainable development and climate change, the construction sector, and in particular the timber industry, is questioning its practices and sources of supply. The use of freshly cut timber in carpentry, validated during the restoration of Notre-Dame, is attracting a growing number of carpenters, not only for the restoration of historic buildings but also for new construction. This potential market, whose development will depend on forestry practices as well as regulatory changes, cannot yet be quantified. Nevertheless, concerted action by professionals, architects, engineers, and scientists can only be useful in convincing people of the merits of this industry and thus supporting its future development.

HEALTH **IMPACT**
(proven impact)

Scientific data on the presence of lead in Paris and the Seine basin, its evolution over time (including before and after the Notre-Dame fire), accompanied by the determination of the isotopic signature of lead from different sources (lead gasoline, Notre-Dame, etc.) enabled the City of Paris to define, in September 2019, an action plan against lead pollution, in line with its Paris Health and Environment Plan. Studies conducted following the Notre-Dame fire demonstrated the importance not only of measuring lead levels in the air, soil, and homes, but also of precisely identifying the source of the lead in order to take appropriate and proportionate measures and respond accurately to the concerns of the population. In addition, the City of Paris and the Île-de-France Regional Health Agency (ARS) are now paying particular attention to the presence of lead in Paris's major historical monuments, in conjunction with the institutions involved in their conservation and restoration.

OUTPUT

Appendices

APPENDIX 1: LIST OF LABORATORIES THAT PARTICIPATED IN THE NOTRE-DAME SCIENTIFIC PROJECT (laboratories under the supervision of the CNRS are highlighted in yellow)

WG	LABORATORIES	SUPERVISORY BODIES	CITY	NUMBER OF SCIENTISTS
ACOUSTICS	CNSMDP	CNSMDP	Paris	1
	Jean-Le-Rond d'Alembert Institute	CNRS / Sorbonne University	Paris	5
	IReMus	CNRS / Sorbonne University	Paris	3
	MSH-UAR2000	CNRS / University of Lyon	Lyon	3
WOOD AND CARPENTRY	AASPE UMR7209	CNRS / MNHN	Paris	6
	BBEES UMS3468	CNRS / MNHN	Paris	2
	Biogeco UMR1202	Inrae / University of Bordeaux	Montpellier	1
	C2RMF	Ministry of Culture	Paris	2
	CICRP	Ministry of Culture / City of Marseille / Regional Council / Departmental Council	Montpellier	1
	Departmental Heritage Conservation	Maine-et-Loire Department	Angers	1
	CR2P UMR7207	CNRS / Sorbonne University / MNHN	Paris	1
	CReAAH, UMR6566	CNRS / University of Rennes	Rennes / Le Mans	5
	Dendrotech	Dendrotech	Rennes / Le Mans	1
	INRAP	INRAP	Paris	1
	Blaise Pascal Institute UMR6602	CNRS / Clermont Auvergne University	Clermont-Ferrand	1
	IPGP UMR7154	IPGP / Paris Cité University / CNRS / University of Réunion / IGN	Paris	1
	IRHT	CNRS	Paris	1
	ISEM UMR5554	CNRS / University of Montpellier / IRD	Montpellier	1
	LAMOP UMR8589	CNRS / University of Paris 1 Panthéon-Sorbonne	Paris	1
	LCE UMR6249	CNRS / University of Franche-Comté	Besançon	4
	LEMTA UMR7563	CNRS / University of Lorraine	Nancy	1
	LIEC UMR7360	CNRS / University of Lorraine	Nancy	1
	LMC14	CNRS / CEA / IRD / IRSN / Ministry of Culture	Gif s/Yvette	1
	LMGC UMR5508	CNRS / University of Montpellier	Montpellier	2
	LRMH UAR3224	CNRS / MNHN / Ministry of Culture	Champs s/Marne	1

WG	LABORATORIES	SUPERVISORY BODIES	CITY	NUMBER OF SCIENTISTS
	LSCE UMR8212	CNRS / UVSQ / CEA	Gif s/Yvette	3
	METIS UMR7619	CNRS / Sorbonne University / EPHE	Paris	3
	MONARIS, UMR8233	CNRS / Sorbonne University	Paris	1
	Navier UMR8205	CNRS / Gustave Eiffel University / ENPC	Champs s/Marne	1
	PIAF UMR547	Inrae / University of Clermont Auvergne	Clermont-Ferrand	1
	SILVA UMR1434	Inrae / University of Lorraine / AgroParisTech	Nancy	3
	University of Liège	University of Liège	Liège	1
MONUMENTAL DECOR	Ausonius UMR 5607	CNRS / Bordeaux Montaigne Univer-sity / Ministry of Culture		1
	André Chastel Center	CNRS / Sorbonne Université / Ministry of Culture	Paris	3
	CRMH Drac IdF	Ministry of Culture	Paris	2
	EA Religion, Culture and Society	Catholic Institute of Paris	Paris	1
	Self-employed (restaurateurs, etc.)		Paris	1
	INP	Ministry of Culture	Paris	1
	LRMH UAR3224	CNRS / MNHN / Ministry of Culture	Champs s/Marne	2
	Ministry of Culture	Ministry of Culture	Paris	1
	Cluny Museum	Ministry of Culture	Paris	1
	Louvre Museum	Ministry of Culture	Paris	1
	Granet Museum	City of Aix-en-Provence	Aix-en-Provence	1
	French Museum Service	Ministry of Culture	Paris	1
	University of Alabama	University of Alabama	USA	1
	University of Bamberg	University of Bamberg	Bamberg	1
EMOTIONS AND MOBILIZATIONS	National Archives/IDPS	Sorbonne Paris Nord University	Villetaneuse	1
	EA4100	Paris 1 Panthéon Sorbonne	Paris	1
	Héritages UMR9022	CNRS / CY Université / Ministry of Culture	Cergy-Pontoise	8
	IDEAS UMR7307	CNRS / AMU	Aix-en-Provence	2
	IIAC Political Anthropology UMR8177	CNRS / EHESS	Paris	1
	Institute for European Studies	University of Paris 8	Saint-Denis	1
	Institute of Social Sciences and Politics UMR7220	CNRS / University of Paris Saclay-ENS / Paris Nanterre University	Gif s/Yvette	1
	LISST-CAS UMR5193	CNRS / University of Jean Jaurès, Toulouse	Toulouse	1
	National Museum	Federal University of Rio de Janeiro	Brésil	1
	Regional Archaeology Service	Ministry of Culture	Paris	1
	SOPHIAPOL EA3932	Paris Nanterre University	Nanterre	1
METAL	ARAR UMR5138	CNRS / University of Lyon II	Lyon	1
	ArScAn UMR 7041	CNRS / University of Paris 1 Panthéon-Sorbonne / University of Paris Nanterre / Ministry of Culture	Saint Denis	2
	CRBE UMR5300	CNRS / University of Toulouse / Toulouse INP / IRD	Toulouse	1
	ICMPE UMR7182	CNRS / UPEC	Créteil	1
	IRAMAT UMR 7065	CNRS / University of Orleans	Gif s/Yvette / Orléans	2
	LCE UMR6249	CNRS / University of Franche-Comté	Besançon	1
	LRMH UAR3224	CNRS / MNHN / Ministry of Culture	Champs s/Marne	2
	LSCE UMR8212	CNRS / UVSQ / CEA	Gif s/Yvette	2
	METIS UMR7619	CNRS / Sorbonne University / EPHE	Paris	1

WG	LABORATORIES	SUPERVISORY BODIES	CITY	NUMBER OF SCIENTISTS
METAL	NIMBE UMR3685	CNRS / CEA	Gif s/Yvette	2
	TRACES UMR5608	CNRS / University of Toulouse II J. Jaures / Department of Culture	Toulouse	1
	TRAME UR4284	University of Picardie JV	Amiens	1
DIGITAL	Archeoscience UMR6034	CNRS / Bordeaux Montaigne University / University of Bordeaux / EPHE	Bordeaux	3
	C2RMF	Ministry of Culture	Paris	2
	André Chastel Center Plemo3D	CNRS / Sorbonne University / Ministry of Culture	Paris	5
	CITERES UMR 7324	CNRS / University of Tours / INSA	Tours	3
	ETIS	CNRS / CY University / ENSEA	Cergy-Pontoise	1
	LASTIG	Gustave Eiffel University / IGN-ENSG / EIVP	Champs s/Marne	2
	LRMH UAR3224	CNRS / MNHN / Ministry of Culture	Champs s/Marne	3
	LS2N	CNRS / University of Nantes / INRIA / IMT-Atlantique / Centrale Nantes	Nantes	1
	MAP UPR2002	CNRS	Marseille	10
	MIS UR4290	University of Picardie JV	Amiens	1
	MOM Ancient Societies Research Federation	CNRS / Universities of Lyon, Saint Etienne, AMU	Lyon	1
	TRAME UR4284	University of Picardie JV	Amiens	1
	ZEMAS	University of Bamberg	Bamberg	1
STONE	ArScAn UMR 7041	CNRS / University of Paris 1 Panthéon-Sorbonne / University of Paris Nanterre / Ministry of Culture	Nanterre	
	ARTHEHIS UMR6298	CNRS / University of Burgundy / Ministry of Culture	Auxerre	1
	Ausonius UMR 5607	CNRS / Bordeaux Montaigne University / Ministry of Culture	Bordeaux	2
	André Chastel Center	CNRS / Sorbonne University / Ministry of Culture	Paris	1
	CHEC EA1001	Clermont Auvergne University	Clermont-Ferrand	1
	CRBC EA4451	UBO	Brest	1
	HisCAnt EA1132	University of Lorraine	Nancy	1
	J. Lamour Institute UMR 7198	CNRS / University of Lorraine	Nancy	2
	IRHIS UMR8529	CNRS / University of Lille	Villeneuve d'Ascq	1
	LA3M UMR7298	CNRS / AMU	Aix-en-Provence	2
	LaMé EA7494	University of Orleans	Orléans	2
	LAMOP UMR8589	CNRS / University of Paris 1 Panthéon-Sorbonne / University of Paris Nanterre / Ministry of Culture	Paris	2
	LISA UMR 7583	CNRS / UPEC / Paris Cité University	Créteil	1
	LRMH UAR3224	CNRS / MNHN / Ministry of Culture	Champs s/Marne	3
	METIS UMR7619	CNRS / Sorbonne University / EPHE	Paris	1
	University of Bamberg	University of Bamberg	Bamberg	1
	University of Cottbus	University of Cottbus	Senftenberg	1
	City of Paris	City of Paris	Paris	1
STRUCTURE	CEGE	University College London	Londres	2
	GC2D EA 3178	University of Limoges	Egletons	4
	GSA	ENSA Paris Malaquais	Paris	2
	I2M UMR5295	CNRS / University of Bordeaux / Arts et Métiers / Bordeaux INP	Bordeaux	7
	Blaise Pascal Institute UMR6602	CNRS / Clermont Auvergne University	Clermont-Ferrand	2

WG	LABORATORIES	SUPERVISORY BODIES	CITY	NUMBER OF SCIENTISTS
STRUCTURE	LGE EA4508	Gustave Eiffel University	Noisy le Grand	2
	LMC2 EA7427	Lyon 1 University	Lyon	2
	LMDC EA3027	University of Toulouse / INSA	Toulouse	2
	LMGC UMR5508	CNRS / University of Montpellier	Montpellier	3
	LRMH UAR3224	CNRS / MNHN / Ministry of Culture	Champs s/Marne	1
	Navier UMR8205	CNRS / Gustave Eiffel University / ENPC	Champs s/Marne	3
STAINED-GLASS	CRC LRMH UAR 3224	CNRS / MNHN / Ministry of Culture	Paris	5
	C2RMF	Ministry of Culture	Paris	3
	André Chastel Center	CNRS / Sorbonne University / Ministry of Culture	Paris	4
	IMPMC	CNRS / Sorbonne University / MNHN	Paris	2
	LGE EA4508	Gustave Eiffel University	Marne la Vallée	2
	LISA UMR 7583	CNRS / UPEC / Univ Paris Cité	Créteil	2
	Soleil Synchrotron	CNRS / CEA	Saint Aubin	1

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APPENDIX 3: PURELY SCIENTIFIC RESEARCH

Beyond the immediate concerns of the construction site, the 2019 fire has sparked fundamental research in various fields of heritage science. Some research focuses more directly on Notre-Dame, while others aim to deepen our understanding of Gothic construction, medieval resources, the environment, the sacredness attached to monuments, and the perspectives offered by digital humanities.

CHRONOLOGY OF THE CONSTRUCTION OF NOTRE-DAME AND HISTORY OF THE BUILDING

Several working groups took advantage of the exceptional access offered by the restoration site to carry out manual surveys from the scaffolding, laser scans, and stone and wood sampling. Thus, the architectural archaeology work carried out by the Stone Working Group, supplemented by dendrochronological analyses by the Wood Working Group, led to a revision of the precise chronology of the medieval construction site. High-definition collected data were carried out on different areas of the cathedral, including the nave and the chevet. Combined with physical and chemical analyses of the stone and wood, these measurements made it possible to identify very precise chronological markers, accurate to within a year: for example, a wooden tie beam at the chevet could be dated to 1171. As a result, the Gothic construction project began earlier than previously thought.

The results also provide information on the sequence of construction and the choices made by the master builders. For example, the collected data have provided a better understanding of the sequence of construction of the bays and how the builders calibrated the geometry of the nave and choir, adapted the flying buttresses, and anticipated certain reinforcements. These studies confirm the great complexity of the Notre-Dame construction project: the documentation now available (photogrammetry, scans, dendrochronological dating markers) provides a new perspective on the sequence of construction phases and the factors that influenced the builders (choice of materials, time constraints, structural innovations).

KNOWLEDGE OF GOTHIC ARCHITECTURE

Several working groups (Stone, Structure, Monumental decorations) took advantage of unprecedented access to the upper areas of the cathedral, as well as the large amount of data collected (laser and photogrammetric surveys, drone photography, etc.), to revisit in detail the principles of Gothic architecture implemented at Notre-Dame. The teams examined the structure of the vaults (morphology, thickness, curvature), the logic of the supports and flying buttresses, and the sometimes unexpected presence of traces of polychromy in the upper parts of the cathedral.

Thanks to these highly detailed digital data, scientists were able to study how the quest for lightness and luminosity characteristic of Gothic architecture was reflected in adjustments to thickness or the use of very slender arches. Structural approaches made it possible to reconstruct the distribution of thrusts and the importance of reinforcements.

These studies led to a symposium at the end of 2023, published in December 2024. They also fed into a broader reflection within the framework of the ANR ALTIOR project (2023—2026), led in particular by members of the Stone working group, which compares Notre-Dame with other Gothic cathedrals such as Sens, Chartres, Bourges, and Amiens.

The aim is to study the "race for height" in France in the 12th and 13th centuries, i.e., how Gothic architects were able to raise the vaults ever higher while preserving the stability of the whole building. The questions focus on the balance between technical innovation (new types of arches, thinner masonry) and the aesthetic and liturgic s to create vast interior spaces (development of verticality, symbolic of elevation). The study of Notre-Dame thus contributes to a better understanding of its place in the Gothic adventure and how the desire for spiritual ascension was translated into the material reality of medieval construction sites.

PROVENANCE OF MATERIALS (MAPPING, SUPPLY)

Research carried out by several working groups (Stone, Wood, Metal) has shed light on the question of the supply of stone, wood, and metal used in the Middle Ages for the construction of Notre-Dame. Based on archival studies, physical and chemical analyses, and isotopic approaches, it has been possible to pinpoint the sites of origin of these different materials.

The Stone WG identified several types of rock from quarries in the Île-de-France region, revealing the logistical challenges involved in transporting sometimes very heavy blocks to the construction site in Paris. Using dendrochronology and isotopic analysis, the Wood Working Group has identified a supply network that is more extensive than previously thought, encompassing forests relatively close to Paris as well as more distant areas. These studies shed light on both the history of forest management (high forests, types of silviculture) ■■■

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and the logistics involved (log driving on the Seine, land transport, selective cutting of young oak trees, etc.). As for the Metal Working Group, it carried out metallographic and chemical characterizations (mechanical tests, isotopic signature) to assess the origin of the lead and iron (staples, fasteners, seals, decorations, cover tables). The results show the existence of several geographical sources, both local and more distant, and confirm the use of reused metal.

Overall, this mapping of resources and flows highlights the organizational skills of the master builders in coordinating a project of this magnitude. Following on from these studies, several teams plan to compare the supply chains of Notre-Dame with those of other Gothic cathedrals in order to better understand the economic dynamics, environmental constraints, and construction strategies that accompanied the architectural boom of the 12th and 13th centuries.

WOOD AND CLIMATE

The oak trees used for the framework of Notre-Dame, precisely dated to the 12th and 13th centuries, constitute a veritable archive of medieval climatic conditions. The Wood Working Group analyzed the structure of the growth rings and their isotopic composition in detail, which made it possible to identify extreme climatic events such as prolonged droughts or periods of intense cold. These results make an important contribution to historical climatology by providing information on climate variations during the period known as the "medieval climate anomaly."

This research is part of the ANR CASIMODO project, led by members of the Wood Working Group. It also provides a better understanding of the consequences of environmental conditions on tree growth and the quality of the wood used in the construction of Notre-Dame. It thus sheds new light on the interactions between climate fluctuations and the exploitation of medieval forest resources.

More generally, the study of the resilience of oak trees in the Paris Basin to successive extreme climatic events (drought and frost) may also contribute to current thinking on forest management, with the potential for these results to be fed back to today's forest managers.

INTEGRATION OF NOTRE-DAME WOOD INTO THE INTERNATIONAL RADIOCARBON CALIBRATION CURVE

The study of the wood from Notre-Dame has provided a unique opportunity to refine radiocarbon dating models on an international scale. The Wood Working Group has conducted a program of intercomparison of radiocarbon measurements carried out by three of its laboratories (LSCE, LMC14, C2RMF) on medieval wood samples taken from the cathedral. This work required the development of protocols for extracting cellulose from wood without altering its carbon-14 content, thus ensuring the most accurate dating possible. Four protocols were tested on samples with different radiocarbon contents, and two of them have already been validated, guaranteeing their reliability for large-scale use.

The ultimate goal is to integrate these data into the international radiocarbon calibration curve, which serves as a reference for refining dating in archaeology and paleoclimatology. The wood from Notre-Dame, precisely dated using dendrochronology and exposed to well-documented environmental conditions, thus constitutes an essential milestone in improving the calibration of radiocarbon ages and refining our understanding of carbon-14 variations over time.

APPENDICES

APPENDIX 4: LIST OF PEOPLE INTERVIEWED DURING THIS STUDY

INTERVIEWS WITH SCIENTIFIC STAKEHOLDERS

PERSONS INTERVIEWED	ROLE
Martine Regert	CNRS Coordinator
Philippe Dillmann	CNRS Coordinator
Aline Magnien	Coordinator, Ministry of Culture and Director, LRMH
Pascal Liévaux	Ministry of Culture Coordinator
Alexa Dufraisse	Wood Working Group Coordinator
Yves Gallet	Stone Working Group Coordinator
Maxime L'Héritier	Metal Working Group Coordinator
Claudine Loisel	Glass and Stained Glass Working Group Coordinator
Dany Sandron	Monumental Decor Working Group Coordinator
Stéphane Morel and the Structure WG	Structure Working Group Coordinator
Livio de Luca	Digital Working Group Coordinator
Mylene Pardoen et Brian Katz	Acoustics Working Group Coordinators
Claudie Voisenat	Emotions and Mobilization Working Group Coordinator

ENTRETIENS AVEC LES ACTEURS NON SCIENTIFIQUES

PERSONS INTERVIEWED	ROLE
Jonathan Truillet	Deputy EP-RNDP to the Deputy Director General
Pascal Prunet	Chief Architect of Historic Monuments
Rémi Fromont	Chief Architect of Historic Monuments
Charles Personnaz	Director of the National Heritage Institute
Carlo Blasi	Studio Comes engineering firms
Matthias Fantin	Bestrema engineering firms
Valery Ossent	Guyenne Medieval Construction Site
Loïc Desmonts	Desmonts Company (Carpentry)
Philippe Giraud	Atelier de la Pierre
Christine Le Goff	ZED Production

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