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Industrial archaeoacoustics, methods and applications in heritage safeguarding. The case of the MNACTEC Territorial System project "The Sounds of Industry"

Emilio Marx[1], Ginebra Raventós de Volart[1], Edgardo Gómez Ortiz[1]

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Abstract

Archaeoacoustics, an interdisciplinary field that combines archaeology, acoustics and computer modeling, traditionally researches the sonic dimensions of ancient cultures, revealing insights beyond conventional methods. This article, however, extends these techniques to the preservation of industrial heritage based on a critical heritage perspective. By focusing on the MNACTEC museum network's project "The Sounds of Industry", it illustrates how capturing, analyzing and recreating the sounds of the industrial past can enhance heritage conservation. By providing immersive auditory experiences, archaeoacoustics presents a unique method for connecting contemporary audiences with the industrial past. This study underscores the potential of sound-based heritage projects to deepen public understanding and appreciation of historical narratives.

Keywords: auralization; museology; critical heritage studies; acoustic heritage; sound heritage; heritage safeguarding

Resum. *Arqueoacústica industrial, mètodes i aplicacions en la salvaguarda del patrimoni. El cas del projecte «Els sons de la indústria» del sistema territorial MNACTEC*

L'arqueoacústica, un camp interdisciplinari que fusiona l'arqueologia, l'acústica i el modelatge informàtic, investiga tradicionalment les dimensions sonores de les cultures antigues i revela coneixements més enllà dels mètodes convencionals. Aquest article, no obstant això, estén aquestes tècniques a la salvaguarda del patrimoni industrial des d'una perspectiva de patrimoni crític. En centrar-se en el projecte «Els sons de la indústria» de la xarxa de museus MNACTEC, il·lustra com el fet de capturar, analitzar i recrear els sons del passat industrial pot millorar la conservació del patrimoni. En proporcionar experiències auditives immersives, l'arqueoacústica presenta un mètode únic per connectar el públic contemporani amb el passat industrial. Aquest estudi subratlla el potencial dels projectes patrimonials basats en el so per aprofundir en la comprensió i apreciació públiques de les narratives històriques.

1. Acoustic Heritage Collective. acousticheritagecollective@gmail.com. https://orcid.org/0000-0002-0909-6606; https://orcid.org/0000-0002-4645-4898; https://orcid.org/0000-0001-8066-2781

Paraules clau: auralització; museologia; estudis crítics del patrimoni; patrimoni acústic; patrimoni sonor; salvaguarda del patrimoni

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1. Introduction

Industrial archaeoacoustics is an innovative, interdisciplinary approach that combines archaeology, acoustics and computer modeling to explore and preserve industrial heritage. It extends the traditional focus of archaeoacoustics, which researches the sonic dimensions of ancient cultures, to the industrial era. By examining the auditory features of historical industrial sites, industrial archaeoacoustics provides unique insights into the social dynamics and cultural transformations that accompanied industrialization.

This article seeks to ascertain whether an understanding of the role of sound and the study and preservation of industrial archaeoacoustics is a necessary and valuable component of the process of ensuring the correct and complete preservation of industrial heritage.

The significance of sound in industrial contexts is underscored by its impact on daily life and work. The clatter of machinery, the hum of factories and the cacophony of urban centers were not mere background noise; they were integral to the experience of industrialization. Understanding these sounds not only enriches our historical narratives and offers a deeper appreciation of the conditions and experiences of those who lived and worked during this transformative period but could also deliver new ways to interpret our present.

Barry Blesser's concept of "aural architecture" is pivotal to understanding how industrial acoustic spaces influenced the behavior, communication and well-being of workers. Blesser's insights into the interplay between sound and space emphasize the need to consider acoustic properties in cultural studies (Blesser & Salter, 2007: 67-68). The unique soundscapes of industrial settings, with their high noise levels and distinctive auditory features, shaped not only the operational dynamics of these environments but also the social interactions and cultural practices of the communities that lived and worked within them. This perspective enriches our understanding of how acoustic environments influence daily life in industrial settings.

Jacques Attali's theories on noise as a cultural and political force provide a broader context for understanding the significance of industrial sounds. According to Attali, noise is not merely a byproduct of industrial activity but a reflection of power structures, labor relations and tech-

nological ideologies (Attali, 1985: 6). By examining the soundscapes of the industrial revolution, we gain valuable insights into the socio-economic transformations and cultural changes that characterized this period. This approach reveals how the auditory dimension of industrial heritage can serve as a way to explore broader historical and cultural phenomena.

A significant advantage of applying archaeoacoustic methodologies to the industrialization period is that, unlike many archaeological sites, industrial environments are often well-documented through photographs, drawings, narratives and oral testimonies (figure 1). This wealth of data enables past soundscapes to be reconstructed in detail with unprecedented accuracy. In essence, archaeoacoustics functions as a form of reverse engineering aimed at reaching a specific period, situation or process, to enable focused and clearly defined research. Consequently, this approach requires multidisciplinary support to combine, filter and interpret diverse historical sources and ensure precise and reliable results through the methodology.

Figure 1. Interior of the warehouse with looms from Pere Roma's textile factory, "cal pelesquenes". Source: Salvador, A. (1935). Retrieved from <https://xac.gencat.cat/ca/llista_arxius_comarcals/baix_llobregat/documentant-la-industria/index.html>

Sites from our industrial past can be found in varying states of preservation today. Some no longer exist or are in ruins, while others are protected or supported by institutions dedicated to their conservation. These institutions manage to preserve, protect, reuse or reconstruct these sites with varying degrees of success. The same applies to the machinery that once operated within them. Archaeoacoustic methodology can be adapted to any of these particular situations, combining in-situ measurements with computational acoustic simulations based on historical information.

On the other hand, a primary challenge for any methodology based on digital representations of auditory perception of a recreated environment is the complexity of a model that only delivers a unique spatial relationship between sound sources and a receiver within a given space. As a result, any three-dimensional simulation such as VR or 360-degree experiences, should be viewed as the aggregation or interpolation of these unique configurations.

In order to optimize these processes for efficient performance without losing reliability, the initial step requires historical analysis to establish a representative spatial configuration of these elements within the historical context under study. This includes determining the types and quantities of sound sources, their locations, the materials composing the ceiling, floor and walls, as well as the dimensions of the original space. Additionally, identifying the position of the representative listener who best reflects the historical activity, whether a worker or a nearby resident, is essential. Establishing this list of elements and their spatial properties, along with deciding which aspects need to

be measured rather than simulated, constitutes the first stage of an archaeoacoustic methodology. This step is essential for guiding the subsequent phases and ensuring reliable results.

In the following sections, theoretical foundations, methodological approaches, practical applications and a case study in the Catalonia Industrial Museum network are explored, highlighting the potential of the archaeoacoustics to preserve and promote industrial heritage for future generations. By integrating acoustics into heritage conservation practices, we aim to showcase the innovative potential of sound-based heritage projects in deepening public understanding and appreciation of marginalized narratives.

2. Theoretical framework

2.1. Critical heritage studies

This article adopts a critical heritage approach to challenge established narratives, particularly within industrial heritage, by highlighting how archaeoacoustic methodologies can play a vital role in preserving and revealing the industrial soundscapes and auditory experiences that have shaped human history. The Industrial Revolution marked a significant change in societal structures and technological advancements, fundamentally altering the acoustic landscapes of human environments. Sounds associated with industrial processes – such as the clattering of machinery, bustling urban centers and the hum of technological progress – became defining elements of modern life. French economist Jacques Attali famously argued that societal changes can be anticipated through the study of sounds, suggesting that the noises of a society provide early indicators of its future trajectory. This perspective underscores the importance of studying industrial noise to understand societal behaviors and technological advancements that continue to influence contemporary life.

> Everywhere we look, the monopolization of the broadcast of messages, the control of noise and the institutionalization of the silence of others assure the durability of power. (Attali, 1985: 8)

Attali's insights emphasize that sounds are more than background phenomena; they are active agents in shaping societal behaviors and anticipating future developments. Before the Industrial Revolution, there was no formal legislation aimed at controlling noise or public nuisance. The ability to make noise was considered a natural right, reflecting each individual's autonomy. However, as centralized power structures began to emerge, the first legal texts aimed at protecting public peace were introduced. These early regulations marked a shift towards controlling the acoustic environment, reflecting broader changes in social order and governance. Despite these legislative efforts, the ideology and laws concerning public noise were often only nominally opposed to them. While in bourgeois concert settings, silence was meticulously maintained, reflecting the cultural values of the elite, outside these controlled environments there was little effort to enforce silence, suggesting a societal belief that absolute quiet was neither achievable nor desirable (Thurston, 2013: 374).

However, a "dominant heritage discourse", largely influenced by European administrations, is often constructed to

reinforce official narratives of the past (Smith, 2015: 134). For example, in the Catalonian industrial context, heritage tends to emphasize monumentality, technological advancements, economic growth and nationalism. This focus often overshadows marginalized narratives such as industry's direct connections to the proceeds of the slave trade, inhumane working conditions and the brutal treatment of women. In her book *The Uses of Heritage*, Dr Laurajane Smith introduces the concept of the authorized heritage discourse [AHD] to address this issue (Smith, 2006: 29). She later explains this as follows:

> There is a dominant discourse, which I have termed the Authorized Heritage Discourse [AHD]. This professional discourse is often involved in the legitimization and regulation of historical and cultural narratives, and the work that these narratives do in maintaining or negotiating certain societal values and the hierarchies that these underpin. The AHD originated in nineteenth and twentieth century European architectural and archaeological debates over the need to preserve the 'fragile' and 'non-renewable' past for 'future generations' (ICOMOS, 2000). It advocates a 'conserve as found' conservation ethic that assumes that value is innate within heritage sites. In doing so, it privileges material heritage over the intangible, and emphasizes monumentality and the grand, the old and the aesthetically pleasing. This Eurocentric discourse has been taken up, and in turn authorized internationally by organizations such as UNESCO and ICOMOS. (Smith, 2012: 3)

When applied to industrial heritage, archaeoacoustics complements this critical perspective by preserving not only the physical vestiges of history but also the intangible soundscapes that shaped human experiences. By capturing the acoustic characteristics and soundscapes of historical periods of humanity, archaeoacoustics allows for the digital recreation of these environments, offering new ways to engage with and reinterpret the past.

Additionally, acoustic and sound preservation not only challenges the persistent dichotomies within the "authorized heritage discourse," such as natural versus cultural or tangible versus intangible, but also underscores the need to make the concept of "community" and heritage preservation practices more flexible. This methodological fusion enriches our understanding of heritage, fostering public engagement and providing innovative tools for conservation that address intangible dimensions of cultural history.

In the context of our case study on Catalonia and the preservation of industrial heritage, it is important to critically examine how preservation practices have been shaped by institutional priorities and the predominance of visual narratives. While recent history in Catalonia has seen active efforts to preserve cultural heritage, these initiatives have predominantly been led by institutions, primarily through museums, and are largely centered on the hegemony of the visual. In the case of industrial heritage, conservation efforts have often focused on preserving empty spaces – such as abandoned textile factories – or broken or obsolete machinery. These machines are sometimes varnished to maintain their visual appearance, yet rendered entirely unusable, inert and silent. Although recent efforts have sought to integrate a sonic context into the history of Catalonia's in-

dustrialization – through oral history recordings or by addressing phenomena such as the hearing loss suffered by many factory workers due to the deafening noise of the machines – there has yet to be a meaningful attempt, prior to the present study, to systematically record and catalog the actual sounds of these machines. Furthermore, the preservation of industrial heritage often remains deeply disconnected from its historical origins, such as the role of Cuban plantations and their involvement with slavery.

2.2. Acoustic heritage

Every space has distinctive acoustic characteristics shaped by its geometry, materials and spatial configuration. Whether a cave, church, prison, home, factory or theater, each environment interacts with sound uniquely, creating an auditory signature that defines its acoustic identity. These characteristics, often simplified as reverberation, are essential elements of human experience and cultural memory.

Acoustic heritage refers to the study and preservation of these sonic environments. However, the term has multiple definitions, depending on the study context (Zhu, Oberman & Aletta, 2024). Rather than being a limitation, this conceptual openness allows for broad research perspectives, discussions and methodologies. In archaeoacoustics, the primary focus is on estimating and preserving the acoustic parameters of a given space through in situ measurements or digital simulations (Murphy & Shelley, 2010).

One of the most effective methods for documenting, archiving and analyzing these parameters is the impulse response, which captures how sound interacts with a space. This can be measured directly in existing or difficult-to-access locations, simulated in the case of lost structures, or combined in cases where original architectural features have changed.

> […] Heritage acoustics uses different measurement techniques, in particular impulse responses to document how sound reacts in a specific space. Anyone who's stepped into any cathedral or concert hall and clapped their hands or whistled and listened to the reverb trail off has, at a very elementary level, conducted an impulse response. (Markus, 2022)

An impulse response functions as a digital filter incorporating all the echoes produced by a space's surfaces and their temporal behavior across different frequencies (figure 2). As we will see in section 2.4, storing this data enables a space to be experienced indefinitely by convolution reverb, through a process called auralization, making this a fundamental tool for acoustic preservation.

Since an impulse response represents only a single source-receiver relationship, comprehensive studies require multiple measurements or simulations, to build an accurate library of acoustic data. Additionally, archaeoacoustics employs acoustic descriptors such as T60, Clarity50, Speech Transmission Index (STI), Articulation Loss of Consonants (ALcons), Strength (G), Early Decay Time (EDT) and Clarity80 (C80) (Navas-Reascos, Alonso-Valerdi & Ibarra-Zarate, 2023). These descriptors provide quantitative insight into the acoustic environments of historical sites, enriching industrial heritage studies.

Preserving acoustic heritage is achieved through systematic data storage, with auralization serving as the most tangible

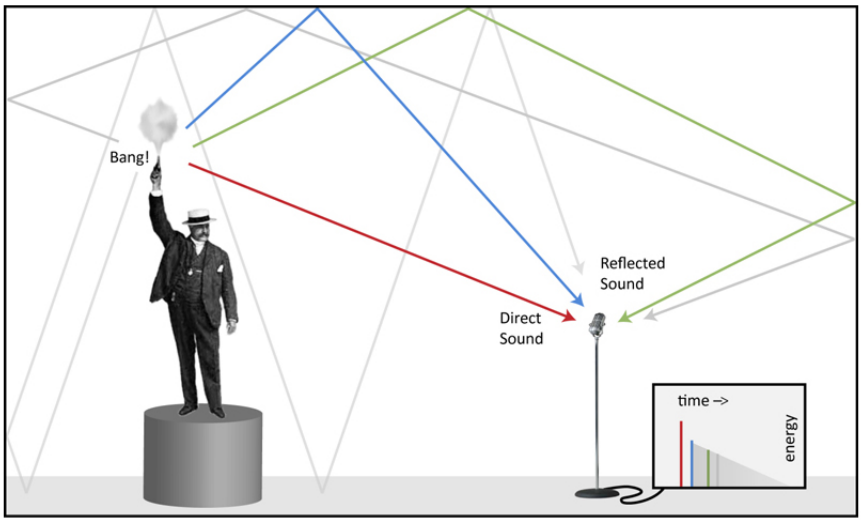

Figure 2. Conceptual illustration of an acoustical impulse [Screenshot]. Retrieved from <https://www.prosoundweb.com/images/uploads/RationalGuideFigure1June2015.jpg>

form of preservation. However, archaeoacoustics has primarily been used for sites of recognized architectural value or those that have disappeared (Navas-Reascos, Alonso-Valerdi & Ibarra-Zarate, 2023). The emphasis on "culturally significant buildings" (Firat, 2021), "important historic buildings" (Brezina, 2013), or "humanity's great architectural sites" (Katz, Murphy & Farina, 2020) raises critical questions about what is deemed "recognized" or "significant."

Beyond physical deterioration, the need to preserve acoustic spaces stems from their role in cultural memory, historical uses and human narratives.

> The fire at Notre Dame Cathedral in Paris in 2019 and the one at Gran Teatro La Fenice opera hall in Venice in 1996 are reminders of the fragile nature of humanity's cultural heritage. Fortunately, acoustic measurements, numerical simulations, and digital reconstructions can recover – and to some extent preserve – the sound of humanity's great architectural sites. (Katz, Murphy & Farina, 2020: 32-37)

These cases highlight the urgency of preserving acoustic data, especially for non-official heritage spaces. Jonathan Sterne critiques preservation guidelines for lacking future-proofing, arguing that archives must actively engage with the present to anticipate future significance (Sterne, 2009). Acoustic heritage, therefore, must not only preserve the past but also adapt to contemporary and future interpretations.

2.3. Sound heritage

The term "acoustic" is often used interchangeably with "sound," "sonic," "acoustical" or "aural" (Zhu, Oberman & Aletta, 2024: 1), which would imply, among other things, that acoustic herit-

age is synonymous with sound heritage. However, as a collective, we aim to distinguish between these concepts for practical purposes, rather than assuming their equivalence. While both terms are complementary, interdependent and part of the same auditory experience, we propose this distinction primarily due to the significant differences in their preservation methodologies, and to facilitate their comprehensive applications. In our understanding, "acoustic heritage" refers to the characteristics of the environment or space in which sound propagates, while "sound heritage" focuses on the sound-producing object itself.

The concept of "sound heritage" began to take shape as scholars and cultural institutions increasingly recognized the importance of sound in preserving and understanding cultural practices, traditions and environments. This recognition grew significantly in the late 20th century, particularly with the rise of audio recording technologies that allowed for the documentation and preservation of sounds.

The formal acknowledgment of sound as an aspect of cultural heritage can be traced back to the 2003 UNESCO Convention for the Safeguarding of the Intangible Cultural Heritage (UNESCO, 2003a). This convention expanded the definition of cultural heritage to include intangible aspects such as oral traditions, performing arts, social practices and other forms of cultural expression. Sound heritage, therefore, became increasingly recognized within the broader framework of intangible cultural heritage, emphasizing the importance of preserving not just the physical artifacts of culture but also its auditory elements that are integral to cultural identity and memory.

2.4. Auralization

The safeguarding of acoustic and sound heritage is fundamentally a form of heritage digitization, in which physical sound phenomena are captured and preserved as digital files. This digitization enables the creation of accurate spatial audio experiences through a process known as auralization.

> This process, called Auralization, which is an analogy to virtualization but in the auditory domain, is defined as the technique of reproducing audio from numerical data (simulated, measured or synthesized). (Vorländer, 2008: 3)

In archaeoacoustics, auralization enables the recreation of historical soundscapes by simulating both sound sources and their interaction with the acoustic environment. This process accounts for factors such as distance, directionality, reverberation and obstacles, thereby enabling a highly realistic auditory simulation in a binaural format.

To fully grasp the methodology presented in this article, it is essential to explore foundational theoretical acoustical concepts. Our approach follows Barry Blesser's "aural architecture" theory, which posits that auditory perception consists of two complementary elements: sound and space (Blesser & Salter, 2007). Sound requires a medium to propagate, just as the medium needs sound to be activated. Conceptually, an acoustic space functions as a filter that modifies sound during its propagation. Although sound and medium overlap in human perception, they can be documented separately – the former through sound capture and the latter through acoustic filtering.

This distinction is important because the human brain processes these elements separately, decoding the sound message while simultaneously interpreting spatial and locational cues. For example, walking into a cathedral at night, one can perceive the shift from a narrow entryway to a vast nave through the reverberations of footsteps and speech, even in complete darkness. This phenomenon, described by Teng et al. (2017: 2), illustrates how the brain separates auditory sources from their reverberant spaces to extract environmental information.

Auditory perception plays a critical role in how humans create a sense of spatiality. Our brains unconsciously determine the direction of sounds through minor delays between the ears, and gauge the dimensions and materiality of spaces by analyzing sound reflections. This capability is so integral to our spatial awareness that individuals in anechoic rooms, which are devoid of reverberation, often feel disoriented after a short period of time. Recent behavioral studies suggest that the auditory system can separate natural reverberation from its source to analyze environmental information, although the neural basis of this process remains largely unexplored (Traer & McDermott, 2016).

Another fundamental property of sound and space is their ability to evoke emotion and memory. This aspect is particularly relevant in a heritage context, as it links auditory experiences with memory and identity. Numerous studies have documented the emotional responses elicited by sounds (Bradley & Lang, 2000: 207), emphasizing that acoustic elements are significant to communities and deserve preservation as part of cultural heritage.

This study is situated at the intersection of several emerging academic disciplines that recognize the importance of sound and the aural environment of the past.

3. Methodology

The methodology deployed in this study is based on the theoretical framework described above, and integrates various archaeoacoustic techniques to safeguard, study and publicise industrial heritage. These methods are tailored to capture, analyze and recreate the sounds produced by obsolete machinery and by acoustic environments shaped by industrial activities, providing a comprehensive understanding of their acoustic characteristics and their significance in heritage conservation but also helping to understand social processes through the study of noise and acoustics. Historically, industrial noise was not merely a by-product but a defining characteristic of urban life, offering insights into technological advancements and societal changes. This methodology is also designed to deliver results mainly consisting of audio banks that can be easily incorporated into further studies or distribution strategies. Some industrial spaces still possess original machines that function adequately; however, many of them no longer operate with the original raw materials. The study aims to answer three key questions:

1. How do we determine original architectural properties in order to ensure our analysis is reliable?
2. How do we evaluate the difference in sound between the mechanism of a spinning machine and the same machine loaded with threads?

3. Is it possible to simulate this sound from an existing recording? Can we recreate the sound of 50 machines from the recording of one machine?

These kinds of considerations and decisions necessary for the appropriate representation of a lost sound space do not have a single answer. They depend more on the objectives, feasibility and availability of resources than on a single formula.

3.1. Industrial acoustic heritage preservation methodologies

Industrial acoustic heritage preservation involves a meticulous approach to documenting, preserving and communicating the acoustic properties unique to industrial spaces.

This process includes capturing impulse responses to understand how sounds interact with the various surfaces in industrial spaces such as walls, ceilings and floors (figure 3). These recordings require precise measurement techniques ranging from advanced equipment compliant with ISO standards (ISO, 2009: part1) to simpler validated methods such as triggering acoustic events like balloon pops or pistol shots. They provide the basis for digital recreations of the auditory environment (Abel et al., 2010: 1). The ideal scenario of acoustic spaces that still exist in their original condition is not common. Thus, de-

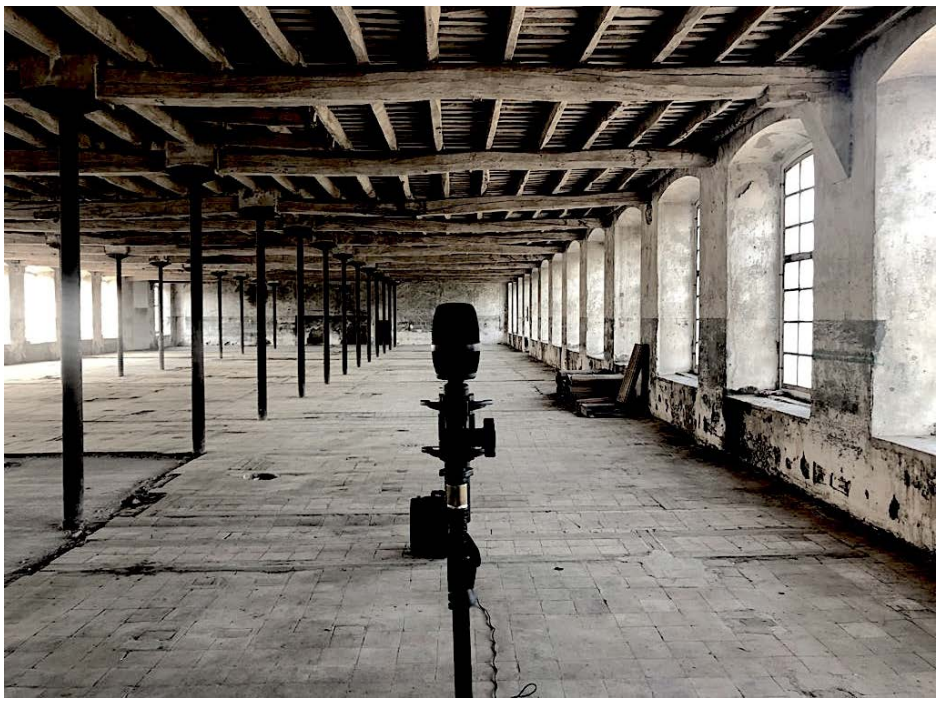

Figure 3. Recording industrial site. Source: Raventos (2023). Retrieved from <https://acousticheritagecollective.org/archivomnactec/index.html>

pending on the difference between the present condition of an industrial space and its original characteristics, digital acoustic models are required, to determine the same acoustic parameters that could be measured in ideal conditions.

By analyzing this and various other acoustic descriptors derived from archaeoacoustic applications of room acoustics such as reverberation time, clarity, speech transmission index, articulation loss of consonants, strength, and early decay time, researchers can obtain a reliable simulation of the desired acoustic environment. This is essential for understanding the spatial characteristics and ambiance of industrial sites.

The acoustic data and digital models will also contribute to interdisciplinary research, providing valuable resources for historians, archaeologists, psychologists and acousticians, leading to a deeper understanding of the role of sound in industrial heritage and its impact on human experiences. By achieving these outcomes, acoustic heritage preservation efforts will significantly contribute to the preservation and understanding of industrial heritage, ensuring that the sounds of the past are accurately documented and appreciated by future generations.

3.2. Industrial sound heritage preservation methodologies

In contrast, industrial sound heritage preservation methodology focuses on the collection and preservation of sound sources associated with industrial heritage. This involves a multifaceted approach to capturing the authentic auditory experiences of historical industrial environments, ensuring that both the mechanical and human elements of these soundscapes are preserved for future study and appreciation.

The industrial era introduced new sounds – factories, clattering machines, bustling urban centers and the hum of technological progress – that came to define modern life. These auditory changes were not merely byproducts of industrialization but integral elements shaping social interactions and cultural norms. Studying these sounds allows researchers to trace the evolution of social structures and predict future changes.

It is therefore essential to consider a range of potential sound sources, including various types of machinery found in factories and workshops, such as looms, engines and presses. External sounds, such as the presence of a nearby river or the movement of vehicles outside the industrial facility, could also significantly influence the overall acoustic environment (figure 4).

Figure 4. Panoramic view of Sant Feliu de Llobregat. Source: Unknown. (1905). Retrieved from <https://xac.gencat.cat/permalink/684bb363-7280-11e5-81a0-005056924a59?__scale=h:361,w:640&time=1444988886081>

Workers themselves could also be significant contributors to the soundscape. The noises generated by their movements, actions and interactions with each other added to the overall auditory experience. For example, footsteps,

conversations and the sounds of tools being used were common in industrial settings. More in-depth studies might even explore how language and communication have evolved over the past century, not only in terms of the words spoken but also how they were spoken. Questions arise about whether these elements can be simulated today, whether sufficient information is available, and whether it is necessary for creating an accurate historical soundscape.

Nonetheless, the archive of recordings or simulations of sound sources from an industrial space or process forms a highly valuable resource. This archive allows researchers to listen to, preserve and study specific industrial sounds in isolation from other noises. The more detailed the recordings of machinery, captured using various microphones and positions, the more possibilities there are for subsequent applications in research and for public circulation.

In practice, the proposed methodology begins with recording or recreating the sounds produced by various industrial machines and processes. In the case of well-preserved machinery or industrial processes, high-quality recording equipment is used, strategically positioned to capture the full range of acoustic details. This includes capturing airborne and structure-borne sounds to ensure that all aspects of the machinery's operation are documented. Even for recreations based on sound synthesis strategies, the goal is to create a comprehensive and accurate representation of the sounds as they were originally experienced (figure 5).

Oral testimonies from former industrial workers could also be collected as part of this effort. These testimonies provide invaluable insights into the auditory environment of industrial sites from a human perspective. Workers can describe the sounds they heard daily, the changes in these sounds over time, and their personal experiences within these environments. These oral histories add a crucial personal and human dimension to the sound archives, preserving not just the mechanical noises but also the lived experiences and perceptions of those who worked in these spaces.

Figure 5. J. Comas, former worker at the Museu de la Torneria de Torelló. Source: Raventos (2023). Retrieved from <https://acousticheritagecollective.org/archivomnactec/index.html>

The recordings should be meticulously documented and categorized using detailed metadata, including information about the recording conditions, the equipment used, the specific characteristics of each sound, and the context in which the sounds were captured. This information ensures that the recordings are well-documented and accessible for future use and comparison, and should be saved on detailed technical sheets for each audio file. These sheets provide in-depth information on the recording process, such as the positioning of microphones, the environmental conditions during the recording, and any other relevant technical details.

This comprehensive documentation ensures the accuracy and reproducibility of the recorded data, making it a valuable resource for researchers and practitioners.

3.3. Industrial acoustic and sound heritage communication and promotion strategies

Beyond the importance of creating the archive itself, heritage preservation requires comprehensive and effective strategies to publicize these results. The publication and promotion of industrial heritage involves making the documented sounds and their significance accessible to a wider audience. This includes developing experiences that recreate the acoustic environments of historical industrial sites. Immersive experiences allow users to explore and interact with industrial soundscapes in a highly engaging manner.

As discussed above in the theoretical framework, a pivotal component of circulating and promoting both acoustic and sound industrial heritage is auralization. By recreating the sounds of machinery, workspaces and industrial processes, auralization enables people to connect with history in a profound and sensory manner, thereby enhancing reflexive educational and emotional engagement. By simulating the spatial distribution and acoustic characteristics of past environments, auralization bridges the gap between historical research and the public appreciation of industrial heritage.

Heritage digitization has been underway since the onset of the digital era. However, in recent years, official initiatives (e.g., UNESCO, 2003b), rapid technological advancements, and the urgency brought on by the COVID-19 pandemic have significantly accelerated the development of digital platforms for heritage management. This acceleration has led to increased public and private funding for innovations in online cultural experiences for which acoustic simulation has significant potential, including VR, AR and web-based platforms. In this context, industrial archaeoacoustics presents a valuable opportunity to play a crucial role in the promotion and spread of industrial heritage.

4. Case study: MNACTEC Museum Network, "The Sounds of Industry" Project

The project *Els Sons de la Indústria - Arxiu del patrimoni acústic i sonor de la industrialització a Catalunya* [The Sounds of Industry – Archive of acoustic and sound heritage of industrialization in Catalonia] is an ongoing practice-based research project that collects sounds from the territorial network of the National Museum of Science and Technology of Catalonia (MNACTEC). The project aims to preserve the noises and acoustic spaces that shaped the Industrial Revolution by recording the sounds of the ancient machinery of the network's museums, as well as the impulse responses recorded in their acoustic spaces. The result is an open on-line catalog of lost industrial noises and spaces.

"The Sounds of Industry" acts as a sonic time capsule that brings together the auditory landscapes of Catalonia's history of industrialization. It also presents the contemporary soundscapes of museums and centers dedicated to preserving this vital heritage. Within these recordings, you can immerse yourself in the auditory tapestry of various machines and environments, all of which are associated

with museums and centers affiliated with the National Museum of Science and Technology of Catalonia (MNACTEC).

The project invites the user to explore and listen, as these sounds provide a unique window into Catalonia's industrial past and the enduring echoes of its industrial legacy. As human activities shape the soundscapes of our lives, the sounds we create shape our societies and behaviors. The industrial soundscapes of the late 19th and early 20th centuries were filled with the noises of steam, metal and oil. The inhabitants of those soundscapes lived among those sounds, and their identities were connected to them. Today, many heritage machines and sites lie silent, abandoned or transformed into museums, waiting to be awakened.

4.1. MNACTEC geographical network

The geographical network of the National Museum of Science and Technology of Catalonia (MNACTEC) is a unique museological initiative that explains the various fields and processes of industrial society throughout Catalonia, specifically where they have been most significantly developed. The museums and heritage centers that make up the network describe industrialization in Catalonia through their collections and/or the museological treatment of the various now-obsolete activities or traces that make up our industrial heritage.

Each of the sites in the network is unique, and aims to conserve, research and enhance the movable and immovable heritage it preserves in order to analyze a different aspect of industrialization in Catalonia. Together, the MNACTEC geographical network aspires to provide the optimum museographic explanation of the industrialization process in Catalonia, making it one of the key assets of contemporary Catalan culture, as well as a great resource for the communication of the values of innovation as a social and economic driver. For this project, 24 of the network's museums throughout Catalonia were recorded in-situ over a period of two years (figure 6).

4.2. Case study: methodological implementation

The methodology chosen for preserving acoustic heritage involved capturing spatial impulse responses using an ambisonic microphone, employing both the sweep technique and balloon popping at predetermined positions within industrial spaces. Additionally, industrial machines and processes were recorded simultaneously using from four to six different types of microphones (figure 7). Audio files of the recordings were then imported onto a computer, where they were edited and exported as both mixed tracks and individual tracks for each microphone recording. The following equipment was used to implement this recording system effectively:

— Geophone: Tailored for field recordings, it translates surface movement (velocity) into audio.
— Ambisonic microphone: Designed to capture audio in a 360-degree field for subsequent decoding and playback through various speaker or headphone setups.
— Contact microphone: Captures sound by physically contacting the sound source, converting its mechanical vibrations directly into audio.
— Hydrophone: Specifically engineered to capture underwater sound.

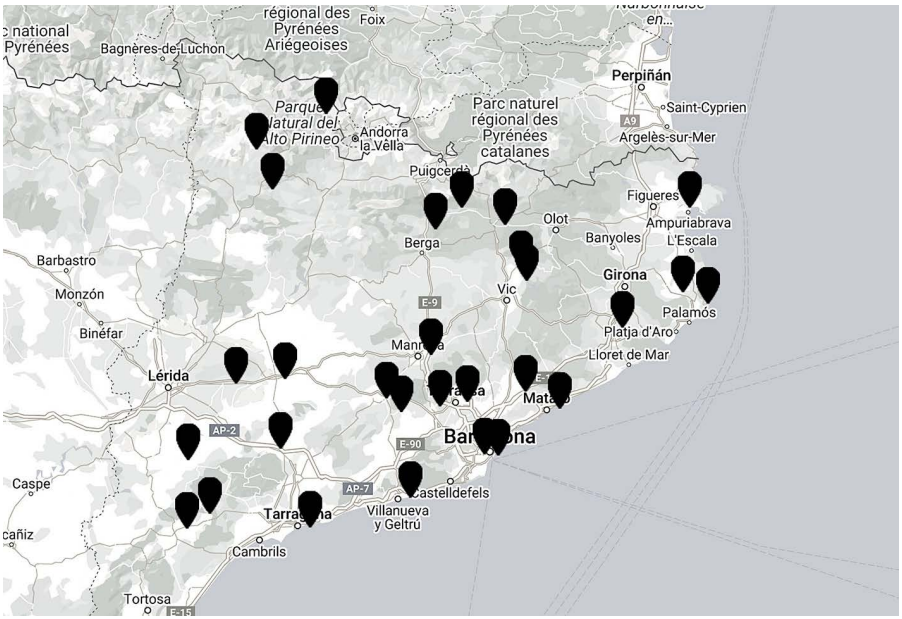

Figure 6. MNACTEC map [Screenshot]. Retrieved from <https://sistema.mnactec.cat/museus/>

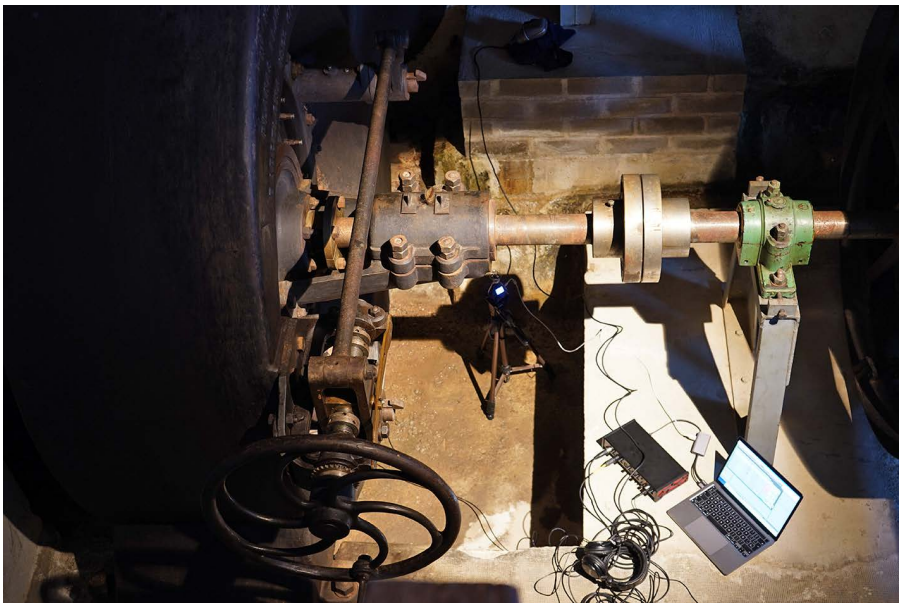

Figure 7. Ecomuseu Farinera de Castelló d'Empúries. Source: Raventós, Marx & Klenner (2023). Retrieved from <https://acousticheritagecollective.org/archivomnactec/index.html>

— Cardioid condenser microphone: Records sound in a single monaural signal, collecting and blending all sound sources into a singular audio output.
— Electromagnetic microphone: Utilizes an induction coil to detect electromagnetic fields and transform them into audible sound.
— X/Y stereo microphone recorder: A stereo recording configuration that enhances the realism and spatiality of sound by using two microphones placed side by side at a 90-degree angle to each other.
— Zoom F6 - Multi channel field recorder + power bank.
— Macbook pro + Reaper software + Max software + HISS tools + Focusrite 4i4.
— Portable full range speaker for sweep reproduction + 46cm Balloons.

4.3. Case study results and outputs

"The Sounds of Industry" project, carried out across 24 museums that together describe the industrialization process in Catalonia, has successfully generated significant quantitative outputs that contribute to the preservation and circulation of Catalonia's acoustic heritage. The project delivered a comprehensive downloadable library of acoustic resources (sweep and balloon pop), which includes 142 stereo impulse responses (binaural decoded) and 175 individual microphone impulse responses comprising spatial, cardioid mono and contact microphone recordings. Additionally, a downloadable sound heritage bank was created, featuring 180 stereo audio samples of industrial machinery (binaural decoded) and 175 individual microphone audio samples, employing a variety of recording techniques including spatial, cardioid mono, contact, electromagnetic and geophone recordings. Furthermore, the project produced detailed text and graphic documentation in the form of 24 documents that include images, contextual information, museum descriptions, methodologies and technical recording sheets, providing a thorough overview of the project's scope and execution.

4.3.1. The online platform "The Sounds of Industry"[2]

The *platform The Sounds of Industry – Archive of acoustic and sound heritage of industrialization in Catalonia* aims to bring together the archive comprising the sound and acoustic recordings of the 24 museums in the network of geographical network of the National Museum of Science and Technology of Catalonia (MNACTEC) and to offer an open tool for all types of audiences to engage with and explore the sounds of the various machines and spaces in the museums and centers affiliated with the MNACTEC network. Besides listening to the archive, members of the public can download the material for non-profit uses, thus inviting interaction with the collective sound memory of Catalonia's industrial past and enabling it to be used as a study tool or creative resource.

The archive is an open online catalog. The recorded sounds are available to users interactively. Users can experience the acoustics of these industrial spaces using a technique called auralization, which simulates the acoustics of a space using a filter (convolution reverb) that modifies the input signal (user's microphone), allowing

2. <https://acousticheritagecollective.org/archivomnactec/index.html>

the listener to experience their own voice as if they were inside that space. The recorded sounds can also be manipulated with a system of faders that allow the user to listen to the machinery and industrial processes with different types of microphones (hydrophone, ambisonic, electromagnetic, geophone, etc.) depending on the type of source and context.

The website consists of a homepage, a download page with the complete sound and acoustic archive of the 24 museums, a page detailing the project description, a sound heritage page and an acoustic heritage page for each of the 24 museums that are part of "The Sounds of Industry" project archive. There is also the option to switch the language from Spanish to English (figure 8).

On the homepage, there is a project description, a one-minute introductory video featuring images and sounds of machines and spaces that are part of the archive, a list of the 24 registered museums, and a map of Catalonia showing the locations of the different museums. When the user clicks on a museum from the list or the map, an image of the museum appears, along with descriptive information about the museum and the option to access its sound heritage or acoustic heritage.

When the user selects the option to visit the sound heritage, the page directs them to different machines in the museum, illustrated with a photograph. Here, a mixer allows them to play and pause the recordings, as well as adjust the volume of recordings from the different microphones used to record each machine, such as electromagnetic, contact or ambisonic microphones (figure 9). This not only generates interactivity with the user but also allows them to hear the subtleties or significant changes between microphones, and helps them understand the process by which the sound archive was created.

When the user selects the option to visit the acoustic heritage, the page takes them to the different recorded spaces of the museum, illustrated with a recent photograph. In this case, instead of displaying the impulse response, we opted for an interactive and immersive option that allows the user to speak into their computer's mi-

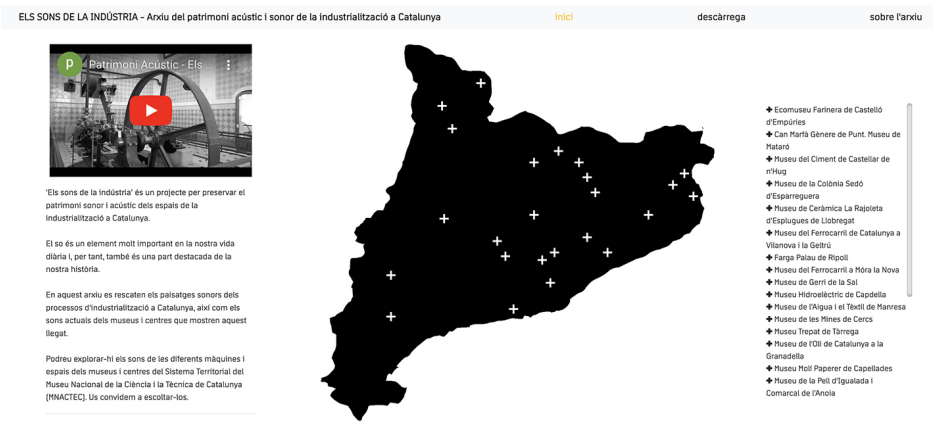

Figure 8. *The Sounds of Industry* homepage [Screenshot]. Retrieved from <https://acousticheritagecollective.org/archivomnactec/index.html>

crophone and hear their voice as if they were inside that acoustic space (figure 10). For this, The ConvolverNode was used. This interface is an AudioNode that performs a Linear Convolution on a given AudioBuffer, often used to achieve a reverb effect. A ConvolverNode always has exactly one input and one output. This tool was especially well received by users because, in general, we have noticed that it is genuinely difficult for a person without prior knowledge of the subject to understand what the acoustics of a space really mean or what convolution reverb is. Of-

Figure 9. Móra la Nova railway museum sound heritage [Screenshot]. Retrieved from <https://acousticheritagecollective.org/archivomnactec/index.html>

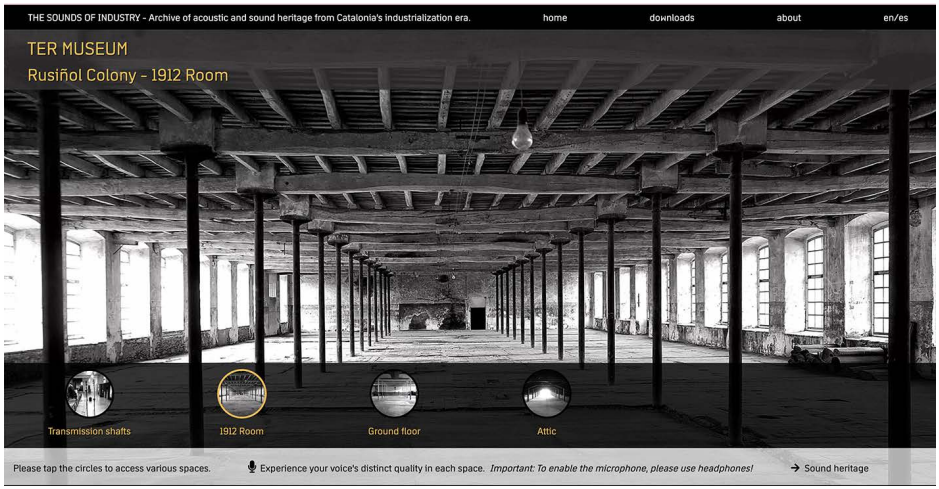

Figure 10. Ter Museum acoustic heritage. Source: Raventós, Marx & Klenner (2023). Retrieved from <https://acousticheritagecollective.org/archivomnactec/index.html>

fering users the possibility to hear how their own voice changes and modifies according to the acoustic properties of different industrial spaces has been a highly valuable tool for enabling anyone to not only understand but also feel and experience these spaces in an immersive way.

Additionally, the website includes a page that provides information about the archive, the process followed to generate it, and the types of microphones used. The website also offers a section that allows users to download the complete archive of the sound and acoustic material from each museum. This archive includes recordings from all the microphones used and a binaural mix of all of them. It also includes impulse responses of the acoustic spaces made with both the balloon method and a sweep made using the HISStoolbox, free software that allows impulse responses of a space to be measured and delivered (Harker & Tremblay, 2012: 148-155). The download also includes a PDF with a description of the archive's content, a description of the museum, a photograph of the space or machine, its technical name, and the microphones or techniques used (figure 11).

When creating the page in collaboration with a public institution, it was very important to prioritize aspects of accessibility and interactivity in the design and user experience. Details such as font size or text justification can be essential to include older people or those with neurodivergence. At the same time, it was essential to convey basic knowledge about sound, acoustics or heritage so that anyone, regardless of educational level or age, could feel connected to the content. For instance, this could be by providing simple explanations about the difference between sound heritage, acoustic heritage and industrial heritage. Another challenge was organizing the large amount of sound material we had gathered. In the end, we opted to select the most relevant material for the website for sonic or historical reasons, while leaving access to the complete archive in the download section.

5. Conclusions

The study of industrial archaeoacoustics highlights the indispensable role of sound in the comprehensive understanding and preservation of industrial heritage. This interdisciplinary approach, combining principles from archaeology, acoustics, history and cultural studies, provides a robust framework for documenting, analyzing and interpreting the acoustic environments of historical industrial sites. This study underscores the necessity of incorporating the auditory element into heritage conservation efforts, to enrich our understanding of the past and ensure the holistic preservation of our cultural history.

The case study of the MNACTEC museum network's "The Sounds of Industry" project exemplifies the practical application and benefits of integrating sound into heritage conservation. This project underscores the importance of field recordings, archival research and public engagement in creating a rich auditory archive that deepens our understanding of Catalonia's industrial past. By capturing and preserving the authentic sounds of industrial machinery and environments, we can provide future generations with a nuanced appreciation of the technological and social dynamics that characterized the industrial era.

The methodologies for preserving industrial acoustic and sound heritage out-

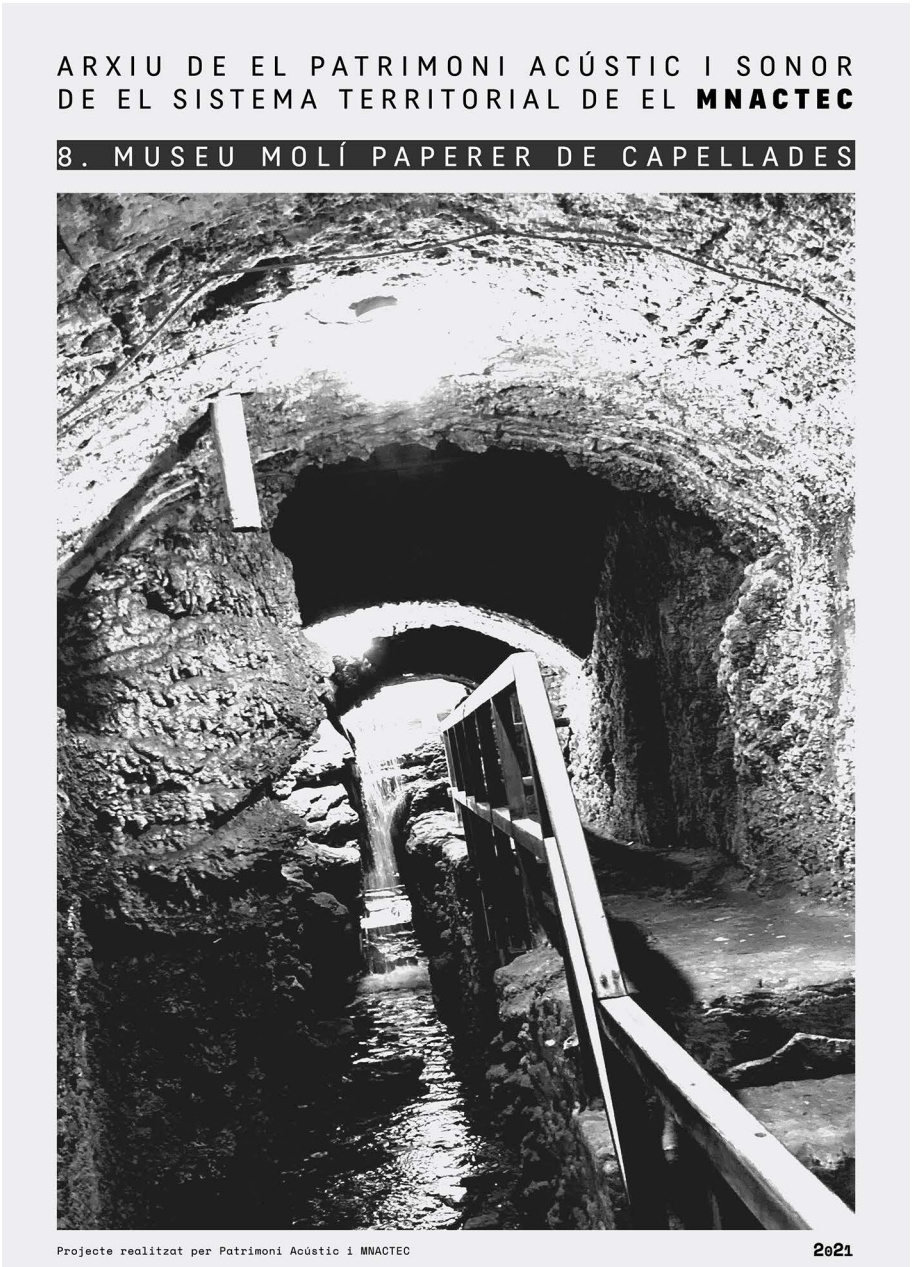

Figure 11. Sons de la Indústria: Capellades Paper Mill Museum. Source: Raventós, Marx & Klenner (2023). Retrieved from <https://acousticheritagecollective.org/archivomnactec/index.html>

lined in this study are expected to yield significant outcomes, both in terms of preserving the historical soundscapes of industrial sites and enhancing public engagement with this aspect of heritage. By implementing these methodologies, the study anticipates achieving comprehensive documentation and preservation of industrial sounds, which will serve as a valuable resource for researchers, historians and the public.

Expected results of the industrial acoustic heritage preservation methodologies (Section 3.1) include the creation of a comprehensive library of impulse responses that capture the acoustic characteristics of various industrial spaces. This library will be complemented by detailed metadata and technical sheets, ensuring that the recorded data is thoroughly documented and easily accessible. Additionally, the development of 3D models and audiovisual documentation will facilitate the digital recreation of historical soundscapes, allowing for immersive experiences that accurately represent the auditory environments of the past. These efforts will not only contribute to a deeper understanding of industrial heritage but also support interdisciplinary research, fostering new insights into the role of sound in historical contexts.

The focus of the industrial sound heritage preservation methodologies (Section 3.2) is on capturing and preserving the authentic auditory experiences of industrial environments. Expected outcomes include the development of a multichannel machinery and industrial process sound bank that captures the full range of sonic details associated with industrial machinery and processes. This sound bank will be accompanied by extensive metadata, audiovisual documentation and detailed technical sheets, ensuring that the recordings are well-documented and reproducible. Oral testimonies from former industrial workers will add a human dimension to the sound archives, preserving not only the mechanical noises but also the lived experiences and perceptions of those who worked in these spaces.

Finally, through its industrial acoustic and sound heritage communication and promotion strategies (Section 3.3), the study anticipates the creation of interactive digital sound archives and VR/AR experiences that will enable the public to engage with industrial heritage in a highly immersive and interactive manner. Educational programs and workshops will raise awareness of the importance of industrial heritage, while public engagement initiatives will involve local communities in the preservation process, strengthening their connection with their heritage. Additionally, the integration of historical industrial sounds into public spaces will create a sense of place and historical continuity, making industrial heritage more accessible to the public. These efforts will be supported by interdisciplinary research, promoting collaboration across fields to develop innovative strategies for preserving industrial heritage.

The exploration of potential further applications underscores the transformative impact that archaeoacoustic methodologies can have on industrial heritage preservation and public engagement. These proposed initiatives offer a roadmap for enhancing the emotional and educational connections between communities and their historical environments. They include:

— Acoustic memory: Studying the capacity of former workers to recall

and emotionally respond to simulations of the reverberant sounds of industries where they were employed.
— Spatial physical installations: Designing onsite installations that allow visitors to interactively engage with acoustic environments through real-time audio signal convolution with the original impulse responses of specific industrial spaces.
— Virtual guides: Incorporating 360-degree or 3D virtual guides on the MNACTEC network website with acoustic simulations that change as the user navigates the virtual space.
— Sounding physical edition: Creating a vinyl-book edition that includes audio samples along with graphical and textual research materials, appealing to various audiences including noise enthusiasts, historians and music producers.
— Public experimentation and creativity: Encouraging public engagement through open calls for musicians and artists to experiment with and create new works from heritage audio banks, fostering a living connection to heritage.
— Heritage gamification: Integrating game-design elements into heritage experiences to engage and educate audiences, enhancing their understanding and connection to cultural and historical narratives.
— Health-related studies on industrial archaeoacoustics data: Further studies on industrial acoustic heritage safeguarding exploring in depth the relationship between acoustics and its impact on hearing loss, cardiovascular health issues and the precarious working conditions associated with industrialization.

These applications not only enrich the preservation and interpretation of industrial soundscapes but also ensure that heritage conservation remains dynamic, inclusive and accessible. By leveraging technology and people's involvement, these methodologies can create immersive, interactive and educational experiences that highlight the significance of industrial acoustic environments.

The study of industrial archaeoacoustics not only broadens our understanding of historical industrial environments but also highlights the importance of sound in shaping human experience and cultural heritage. By preserving and interpreting the sounds of the past, we can provide a more comprehensive understanding of industrial history, emphasizing the vital role of sound in the cultural and social dynamics of industrial societies. The methodologies and applications discussed in this paper demonstrate the potential of sound to enhance heritage practice, ensuring that the auditory dimensions of history are appreciated by contemporary and future audiences.

In conclusion, the integration of sound into heritage conservation efforts not only enriches our understanding of the past but also ensures the holistic preservation of our cultural history. The innovative methodologies and applications of acoustic heritage, such as those explored in the MNACTEC project, highlight the transformative potential of sound in heritage practice. By using sound, we can create more engaging, immersive and educational experiences that foster a deeper connection to our industrial heritage. This approach not only deepens our engagement with the past but also fosters a sense of continuity and connection to the industrial heritage that has shaped our present and will continue to influence our future.

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