Enhancement and Sustainable Fruition of Cultural Heritage in the Era of Ecological Transition: A Case Study on Open Data and Citizen Science

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Abstract: The doctoral research project focuses on cultural heritage in the Italian context, investigating the correlation between cultural heritage preservation and the ecological transition, emphasizing open knowledge, sustainability and citizen science. Through an interdisciplinary approach the project aims at developing an in-depth case study focused on a museum system and its repository. The study aims at analysing poly-material artefacts through multidisciplinary methodologies in a sustainable context, reaching the goal of the research by means of monitoring biotic and abiotic environmental parameters. Wikimedia infrastructures and communities play a pivotal role in ensuring the accessibility and dissemination of research findings through Open Access and free licensing practices.

Keywords: Cultural heritage, environmental sustainability, citizen science, open access.

1. Introduction

The protection of cultural heritage—and the active involvement of both institutions and citizens in this process—lies at the core of national and international regulations and policy frameworks. Article 9 of the Italian Constitution states that "The Republic promotes the development of culture and scientific and technical research. It protects the landscape and the historical and artistic heritage of the Nation" (Senato della Repubblica, Costituzione Italiana. Testo vigente 2023). According to it, the Cultural Heritage and Landscape Code sets out the essential concepts relating to activities aimed at Italy's Cultural Heritage, i.e. enhancement, conservation and protection (D.lgs. 42/2004). In 1972, UNESCO adopted the Convention Concerning the Protection of the World Cultural and Natural Heritage of Humanity, encouraging international cooperation for

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its conservation and identifying the sites most at risk (UNESCO 1972). In addition, Faro Convention, or Council of Europe Framework Convention on the Value of Cultural Heritage for Society, signed in 2005 by more than 20 States, establishes rights and responsibilities to and for Cultural Heritage, focusing on the promotion of sustainability, accessibility, and democratic participation (Faro Convention Art. 12 2005). To date, the same theme is present in the 2030 Agenda for Sustainable Development signed in 2015 by 193 UN member States. The Agenda defines the '17 Sustainable Development Goals' to be pursued in order to achieve sustainable development, in which, in section 11.4, the need to strengthen efforts to protect and safeguard the world's cultural and natural heritage is emphasised (ONU, Agenda 2030 2015). Climate change poses a significant threat to cultural heritage, which, as a testimony to civilisation, history and culture, must be constantly protected. Rising temperatures, flooding and air pollution are just some of the effects of the phenomenon, the direct consequences of which can be seen in the cultural environment in the archaeological sites, monuments and cities of art (Fabbri and Bonora 2021).

In this frame museums assume a pivotal role in cultural heritage conservation, since, according to ICOM, they represent institutions that researches, collects, preserves, interprets and exhibits cultural heritage (ICOM 2024). Museums' mission to ensure long-term preservation and continued access to cultural heritage is endangered in the ever-changing scenario posed by climate change (Cassar and Pender 2005). Collections enhancement, stated as a central activity for cultural heritage preservations (D.lgs. 42/2004), is becoming an issue in museums, often resulting in accumulation of artefacts stored in repositories, regarded as an underused resource. In fact, most museums' collections are stored in these environments: in a survey proposed by ICOM to museums all over the world it is stated that the majority of interviewed institutions exhibit less than 15% of their collection to the public, and the necessity to increase accessibility to those objects is a common opinion. The demand of bigger spaces collides with the reality of most institutions: the same survey highlights that storage spaces condition is judged to be rather unfavourable by most museums staff, regarding lack of free areas and equipment, as most types of furniture are considered to be in short supply (ICOM 2024).

In this context of conscious use, the significance attributed to repositories is increasing in museums system all over the world, not only for their safety functions, but also as study and research reserves. This change of direction is also reflected by the ever-growing success of "open storage", which allow visitors to access depot's spaces, usually through guided tour, thus increasing cultural heritage awareness and valorisation (Ferruzza and Marras 2020). This and other innovative phenomena aim to increase cultural heritage accessibility, but from preventive conservation point of view, this reality rises new doubts, concerning the material aspect of collection, different environmental conditions and logistic organization. This situation presents a high-risk factor, with potential impact on deterioration dynamics: the joint necessity is to find balance between new demands of accessibility and conservation of artefacts in repositories (Loddo 2018).

Museums embrace several categories of artefacts in their collections, with disparate genesis and consistencies, differentiated based on collections' topic and period. This heterogeneity represents both the richness and complexity of cultural heritage, as it portrays the multi-faceted nature of human identity, while also posing challenges to conservation procedures (Canadelli and Di Lieto 2024). Composite artefacts are present in many museums' collections, as modern synthetic materials are often combined with traditional ones, with heterogeneous productive techniques. Poly-material is one of the only common factors among the heterogeneity of collections, and presents a difficulty for their conservation, as interactions of different material result in complex management choices for conservators, from preventive measures to restorative protocols. Degradation phenomena of these objects are strongly conditioned by complex stratification of different materials and their chemical nature (Zmeu and Bosch-Roig 2022). Usually, the presence of organic materials enhances object's susceptibility to biodeterioration, as these substances represent a potential source of nutrition for heterotrophic organisms (Caneva, et al. 2008). Conservative solution to poly-material artefacts deterioration is not straightforward, as established treatments could be the remedy for the baseline material but cause alteration of the other one (Zmeu and Bosch-Roig 2022). If existing procedures can't be fully and satisfyingly adapted to technical-scientific artefacts conservation, defining new protocols is essential.

The study is framed within the wider context of the ecological transition, addressing the emerging challenges and responsibilities that contemporary conservation practices must navigate in response to dynamic environmental conditions. This research aims to enrich the current academic discussion on the protection of cultural heritage by adopting an analytical perspective focused on the evaluation of biotic and abiotic environmental parameters, alongside the assessment of the preservation state of cultural heritage materials.

The project is part of the PNRR Cultural Heritage initiative Ministerial Decree no. 118 of 02-03-2023 (D.M. 118/2023). The research aims at supporting the Italian cultural institutions and heritage sites in the current phases of dynamic change promoted by the ecological transition. The purpose of the project is going to be achieved through the implementation of a systematic experimentation and the use of tools that, starting from the academic research, will stimulate interaction with civil society (Bertacchini and Pensa 2023), as the third mission activities request. The entire research is based on two fundamental pillars: the accessibility of data, through the application of Open Access, Open Data and Open licences; and the active participation of communities, enabling citizens to become an integral part of scientific research, following the principle of Citizen science. This research investigates the role of open data and citizen science in the protection of cultural heritage. It explores how the integration of open data platforms (Farda-Sarbas et al. 2019) and the active involvement of citizens in scientific research contribute to the preservation and sustainable management of heritage resources.

The implementation of sustainable conservation practices and the adoption of innovative technologies for monitoring and damage prevention in cultural

heritage management are therefore of fundamental importance in the context of the ecological transition of the cultural sector (Marzano, et al. 2024), where museums are increasingly required to make strategic choices—deciding in which areas to invest resources and in which to reduce consumption—according to sustainability principles and environmental priorities. In addition, by combining cultural heritage preservation, open knowledge dissemination, and community involvement, the project highlights the transformative potential of Wikimedia-driven initiatives and tools (Fagerving 2023) in addressing global challenges like climate change, while reinforcing the relevance of cultural heritage in society's ecological transition.

2. Case study

The project aims at developing an in-depth case study which is satisfied and reflected through an interdisciplinary approach.

This study takes the Museo Nazionale Scienza e Tecnologia Leonardo da Vinci (Italy) as its focal point, analysing it through a dual analytical lens: one oriented toward conservation practices, and the other toward fostering active participation via community-driven and Wikimedia-related initiatives. In order to study the correlation between climate change and cultural heritage, the investigation underlying the research project is aimed at: i) analysing the museum practices in the field of sustainability; ii) analysing the effects of climate change contextualised to works exhibited in the indoor environment and iii) defining strategies aimed at heritage protection. The entire project is therefore focused on the accessibility and sharing of scientific data related to cultural heritage, with a focus on scientific reproducibility and involving the active participation by communities.

Museo Nazionale Scienza e Tecnologia Leonardo da Vinci is examined through its distinct cultural heritage contexts, focusing on the repository and the museum system. More in detail, the investigation on the repository is focused on the identification and definition of optimal environmental conditions through the design of a monitoring campaign aimed at examining the biotic and abiotic parameters and the artefacts' surfaces conditions; while the focus on the museum system implies the analysis of the issue related to the sustainability practices applied to the repository environment. These two aspects represent key typologies of heritage topic and offer an opportunity for interdisciplinary analysis of their respective conservation and interpretive frameworks.

2.1 Museum repository

The indoor environment analysed has been identified as a museum repository, that covers a large area and that is characterized by a wide variety of poly-materic objects exhibited, dating back to different historical periods. The environment identified is "*Collezioni di studio*", that is the Museo Nazionale Scienza e Tecnologia Leonardo da Vinci's indoor repository (Museo Nazionale Scienza e Tecno-

logia Leonardo da Vinci, 2021). In addition, the attention towards this cultural institution is due to the fact that in February 2022 it has released data from 20.000 objects of the collections available in LOD form (Linked Open Data) under free CC BY-SA 4.0 Licenses, as part of the national ArCo – Architettura della Conoscenza project developed by the ICCD (ArCo project, 2022). The sheets produced show information at the inventory and at the catalographic level, following ICCD's normative; the 20.000 objects are divided into: artworks and objects (OA); scientific and technological heritage (PST); musical instruments (SM). "Collezioni di studio" is partially open to visitors; it occupies an area of 2.000 m^2, hosting about 8.000 objects consisting of various materials referring to different historical periods. The items are stored into three rooms, named: Motorbike and Red Tent Area, Scientific instruments Area and Ship model Area; all the objects are conserved inside lockers and shelves, or on the ground with supports to prevent direct contact with the floor and ensure stability.

The collaboration has been shaped to follow three principal research lines: environmental micro-climatic and biological monitoring of the exhibition areas, analysing of the state of preservation of poly-materic objects exhibited in relation to the exposure environment (with a specific focus to the metallic ones), and Wikimedia events aimed at updating Wikipedia articles. The cultural heritage data acquired, related to the repository environment monitoring and the state of preservation of the objects under study, will be stored in the Wikibase structure, in order to make research data easily accessible. Wikibase allows to create private istances that can serve as primary sources for data to be later referenced in Wikidata (Rossenova, et al. 2022). The activities planned as "wikiexcursions" and "edit-a-thons" are focused on updating Wikidata and Wikimedia Commons through specific themes focused on cultural heritage and preventive conservation. Within the edit-a-thons, there are also activities aimed at updating specific points or interesting areas of OpenStreetMap (Grinberger, et al. 2022), through the correct geolocation of the big indoor cultural heritage objects under study, such as those on display in the naval and aviation pavilion. The environmental micro-climatic monitoring, thanks to the emerging collaboration with a company that provided sensors, is structured through the placement of 8 pairs of sensors along the perimeter and the centre of the museum repository. The choice related to the location of the sensors within the repository follows a strategy that implies considering the total area of the repository as a "grid", that allows to reconstruct the microclimate of a given limited area. Sensors acquire and record data that can be monitored over time to assess environmental quality. They register both atmospheric parameters (T, RH and Pa) and pollution parameters (PM 1, PM 2.5, PM 4, PM 10, VOCs and CO_2). In addition, the Museum has a microclimate control system that allows monitoring data related to indoor data acquired from 2021 to date in the "Collezioni di Studio" environment, from 3 sensors recording T and RH. Given the possibility to analyse and compare the atmospheric parameters from the previous years to date, an environmental risk model is feasible. A one-year monitoring campaign is now active in order to define the Heritage Microclimate Risk (Historical) and the

Predicted Risk Damage Indices (HMR_{hs} e PRD index), that indicate the microclimate risks and the possibility to reduce material damage (Tringa, et al. 2024).

Alongside biotic environmental component has been preliminary assessed through aerobiological investigation, to assess concentration and abundance of microorganisms able to deteriorate artefacts conserved in museum storage room. Airborne contaminants have been sampled using the method of culture-plate, employing Petri dishes as gravitational samplers, and identified with morphological analysis. This preliminary inspection was necessary to determine the exact protocol to employ during aerobiological monitoring campaign, including sampling location, number and timing. Seasonal monitoring will be conducted with active samplers, employing both culture-dependent and culture-independent techniques for identification, in order to correlate microorganisms' concentration to abiotic environmental factors.

The heterogeneity and poly-materiality of artefacts stored within the "Collezioni di Studio" repository requires the application of multidisciplinary investigation methodologies. For this reason, further biological investigations will be carried out on surfaces of artefacts composed by different materials, which present potential active biodeterioration. Microorganisms will be sampled with sterile cotton swab and both culture-dependent and culture-independent techniques will be employed for identification. Moreover, the investigation of biodeterioration dynamics on artifacts will be conducted *in vitro*, recreating the same materials and conditions of some representative artefacts in laboratory, to assess the interaction between microorganisms and materials, since cultural heritage value seldom admit invasive samplings.

A large number of the items located in "Collezioni di studio" are techno-science-related and include two-wheeled vehicles made of metals and alloys, so the need to set up a diagnostic campaign also focused on metals. For the purpose of evaluating the variation in the state of preservation over time, control samples (carbon steel coupons 2,5x5cm) have been placed in the exposure areas of the museum repository, along the perimeter and the inner exhibition area. The metallic coupons were placed in the Scientific Instrument Area at 11 points of interest and in the Motorbike and Red Tent Area at 8 points of interest. The metallic coupons were placed at both 45° and vertical angles, at two different heights corresponding to those of the shelves with the goods on display. In spring 2025 82 carbon steel coupons have been placed in the selected points of interest in "Collezioni di Studio". Through the acquisition of photos and subsequent periodic visits within two years of research, control samples are analysed with the aim of studying the degradation products, organic deposits, and material loss assessment.

2.2 Museum system

The focus on the museum system reflects the need to thoroughly investigate the internal dynamics of a cultural institution that can gradually lead to the definition of "Green Museum", a cultural entity which fully embodies the princi-

ple of environmental sustainability in the field of Cultural Heritage. A "Green Museum" integrates that principle into its management, exhibition practices and operational activities, with the aim of reducing ecological impact and promoting environmental awareness among the public. This includes energy efficiency strategies, waste reduction, use of sustainable materials and educational programmes focused on sustainability (Brophy, et al., 2008).

The study of the Museo Nazionale Scienza e Tecnologia Leonardo da Vinci is carried out through a multi-dimensional approach, encompassing the examination of sustainability-related guidelines and best practices for cultural buildings, the analysis of HVAC systems (Heating, Ventilation and Air Conditioning system) within the indoor storage facilities, and the investigation of Citizen Science initiatives promoting sustainability in the museum sector. Currently, the museum repository, is also undergoing a rearrangement of part of the collections and the definition of the new indoor heating system. The possibility of analysing the consumptions related to the current HVAC system in the Scientific Instruments Area of "Collezioni di studio" over the course of a one-year campaign, allows to create an actual Life Cycle Assessment model (LCA), a method for assessing the environmental impact, determining its actual potential and the feasibility of energy-saving. Starting from the LCA Inventory of data in the input and output of the system, the model is based on the ISO 14041 standard (ISO 14041) and allows to define a correct strategy, in the face of low energy consumptions (Ge, et al. 2015).

The involvement of Wikimedia communities constitutes a key component of the case study, particularly through the organization of participatory initiatives such as edit-a-thons and writing weeks, aimed at enriching and updating Wikipedia content related to the museum and its themes.

3. Conclusion and future work

This research has the ultimate purpose to develop sustainable strategies and models for the use and wide dissemination of cultural heritage, starting from the current state of the art, intertwining with the common awareness of the fundamental issue of climate change and progressively producing and monitoring data. The project overview emphasises how museums with their already available data and those in the process of being openly released, can be mapped, enriched and interconnected through Wikidata. This approach enables the selection of new relevant data and the updating of an open and accessible information network, fostering the valorisation of cultural heritage. A key component of the project deals with organizing Wikimedia events in order to involve citizens and communities in the current research process. These events aim to raise awareness, share best practices in sustainable heritage conservation, and democratize access to scientific knowledge. Wikipedia, Wikidata, Wikimedia Commons, Wikibase and OpenStreetMap constitute the pillars to assess the entire research project.

The in-depth case study has the purpose to investigate both the environmental sustainability practices applied to museum environments and the main phe-

nomena of heritage degradation, through the analysis of the causes that led to their occurrence. The aim is to monitor and define both the conservation environment of cultural heritage and the degradation phenomena discovered on the surfaces of the materials under analysis. Particularly, due to the poli-matericity of the cultural heritage artefacts exhibit within the "Collezioni di Studio" repository, has been necessary to apply a multidisciplinary strategy. In addition, as a result of the monitoring of all the environmental data acquired and the state of conservation of the works, it is possible to obtain the definition of guidelines and best-practices aimed at the preventive conservation of the historical heritage under study.

This research project offers a contribution to the understanding of methods and practices for the conservation of cultural heritage, aware that three years of experimentation is only the beginning of a process to be carried out on a much longer time scale, in order to assess the impact of climate change on cultural heritage.

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