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Advancing Built Cultural Heritage Conservation: Integration of Industry 5.0 Principles and Enabling Technologies

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Abstract. The emergence of Industry 5.0, following the widespread adoption of Industry 4.0, marks a pivotal shift in digitalization and industrial operations. This article explores the implications of Industry 5.0 principles and enabling technologies within the Architecture, Engineering, Construction, Management, Operation, and Conservation (AECMO&C) industry, with a particular focus on the conservation of built cultural heritage environments. The results obtained from a systematic literature review and an online survey are summarized and discussed. Results reveal that artificial intelligence and digital twins are the most frequently studied enabling technologies in this context, while sustainability emerges as the dominant principle in the discourse surrounding this novel paradigm. Conversely, the principles of resilience and human-centrism remain underexplored, highlighting the need for further research to achieve a holistic implementation of Industry 5.0 in conservation practices. Furthermore, although awareness of Industry 5.0's potential is growing, its adoption in heritage conservation remains limited due to knowledge gaps, inadequate training, and resource constraints. This underscores the need for comprehensive strategies to integrate Industry 5.0 principles and technologies into the conservation of built cultural heritage. Insights presented are intended to guide conservation practitioners seeking best practices, inform policymakers promoting technological adoption, and inspire researchers to address existing gaps and drive further innovation.

Keywords: Industry 5.0 · Human-Centered Approaches · Resilience · Sustainability · Built Cultural Heritage · Heritage Conservation

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1 Introduction

The conservation of built cultural heritage has long been recognized as a fundamental responsibility for societies seeking to preserve their architectural, artistic, historical, and cultural identity. Moreover, conservation can act as an enabler for societies to achieve sustainability [1]. In particular, the Built Cultural Heritage (BCH) encompasses immovable heritage assets, including structures, buildings, landmarks, and spaces of significant cultural and historical value [2]. Over the decades, conservation efforts have evolved to integrate scientific, technological, and multidisciplinary approaches to ensure the longevity and relevance of heritage assets in the face of natural and anthropogenic threats. However, traditional conservation methodologies often struggle to keep pace with rapid advancements in digital technologies [3].

The introduction of Industry 4.0 marked a pivotal moment in the digitalization of industrial and engineering practices, bringing forth technological innovations such as the Internet of Things (IoT), cyber-physical systems, Digital Twins (DT) and artificial intelligence (AI). These advancements have been employed within the built cultural heritage sector to enhance documentation, restoration, and monitoring processes. For example, DT have facilitated improved museum collection management [4] and enhance the management and operation of heritage bridges [5], while extended reality technologies have transformed visitor experiences in cultural sites [6]. Despite these technological strides, Industry 4.0 has been criticized for its limited ability to sufficiently address socio-economic inequalities, and for its environmental impact [7].

In response, the European Union has introduced Industry 5.0 as a transformative paradigm that builds upon the foundations of Industry 4.0 while prioritizing three core principles: human-centrism, resilience, and sustainability [8]. Industry 5.0 shifts the emphasis from purely technological efficiency to a more inclusive, regenerative, and sustainable model of development. Its recognized enabling technologies include AI, DT, human-machine interaction, bio-inspired materials, and energy-efficient systems. While these principles and technologies have been explored in fields such as manufacturing, education, and energy, their integration into built cultural heritage conservation remains limited [9]. There is a pressing need to bridge this gap by fostering interdisciplinary collaboration, adapting conservation methodologies to emerging technological capabilities, and ensuring that Industry 5.0 principles are followed to enhance BCH preservation practices.

Human-centrism in heritage conservation aligns with the participatory and multidisciplinary ethos traditionally advocated by conservation charters such as the Venice Charter (1964) [10]. The integration of human-machine collaboration, AI-driven decision-making, and ethical frameworks for digital heritage documentation can enhance conservation efforts while preserving the integrity of human expertise and traditional craftsmanship [11, 12]. Similarly, resilience in BCH conservation requires proactive strategies to mitigate risks associated with climate change, urbanization, and socio-political instability [13]. Digital technologies such as real-time structural health monitoring, predictive modeling, and AI-enhanced risk assessment can contribute to safeguarding heritage assets from both shock events and long-term stresses. Sustainability, as the third pillar of Industry 5.0, is particularly relevant given the increasing urgency of addressing climate change and resource conservation. Implementing circular economy principles (as long

as they do not speed up renewal cycles or incentivize disassembly for repurposing of historic elements), low-carbon materials, and energy-efficient conservation strategies can ensure that heritage sites remain environmentally and economically viable. Moreover, the role of culture in the creation of sustainable cities has gained increased recognition among decisionmakers [14].

This paper aims to explore the intersection of Industry 5.0 principles and enabling technologies with BCH conservation. By analyzing the latest advancements, identifying existing gaps, and proposing strategic pathways for integration, this research contributes to advancing a more sustainable, resilient, and human-centric approach to heritage conservation. In Sect. 2, the methodology followed to conduct a systematic literature review (SLR) and an online survey is presented. Section 3 discusses the results and analysis of the findings, while Sect. 4 concludes the paper by summarizing key insights.

2 Methodology

This study adopts a dual-method approach combining a SLR and an online expert survey to explore the integration of Industry 5.0 principles and enabling technologies in BCH conservation. Each method was independently conducted following rigorous protocols, as described below. In the present contribution, results from both studies are analyzed and compared to identify convergence and divergence in academic discourse and professional practice. The comparative synthesis aims to provide a comprehensive understanding of current trends, gaps, and actionable insights for the implementation of Industry 5.0 in the AECMO&C sector.

2.1 Methodology of the Systematic Literature Review

The SLR was conducted to examine how Industry 5.0 principles and enabling technologies have been addressed within the context of BCH conservation. The review followed the PRISMA 2020 guidelines [15], and its protocol and search strategy were preregistered and made publicly available on the Open Science Framework [16]. The search was performed on the Scopus database on 16 February 2024, targeting peer-reviewed publications in English from 2020 onwards. Inclusion criteria comprised journal articles, conference papers, book chapters, and reviews related to the themes of human-centrism, resilience, sustainability, and the enabling technologies defined by the European Commission under the Industry 5.0 framework.

Three structured search queries (SQ1–SQ3) were developed using Boolean operators and wildcard characters to capture relevant publications in the domains of Engineering, Social Sciences, Environmental Sciences, and the Arts. After deduplication using EndNote software [17], a total of 872 records were screened by two independent reviewers based on titles, abstracts, and keywords. Discrepancies were resolved by a third reviewer. Records passing the initial screening were retrieved in full and assessed for eligibility, resulting in the inclusion of 78 studies.

The selected studies underwent bibliometric analysis including performance metrics and science mapping. VOSviewer [18] software was used to visualize keyword co-occurrence and co-authorship networks, allowing the identification of thematic clusters.

A narrative synthesis was then applied to interpret the qualitative data, categorizing the selected studies according to the three core principles of Industry 5.0 and the six enabling technologies recognized by the European Commission.

2.2 Methodology of the Online Survey

To complement the insights derived from the literature review with practitioner perspectives, an online survey was conducted targeting professionals involved in the conservation of built cultural heritage. The objective was to investigate the perceptions, barriers, and potential of Industry 5.0 principles and enabling technologies from a stakeholder standpoint. The study employed an exploratory, cross-sectional design using a structured, self-administered online questionnaire.

The survey was created and distributed via Nettskjema, a web-based tool hosted by the University of Oslo. It included a mix of single choice (Likert scale), multiple-choice, and open-ended questions, designed to capture both quantitative and qualitative data. The questionnaire was carefully structured to prioritize engagement, with more interactive items placed at the beginning and demographic questions positioned at the end. All questions were mandatory to ensure data completeness. The full questionnaire can be consulted in [9].

Questionnaire testing was conducted in two phases. First, co-authors reviewed the initial version to assess clarity and logic, after which minor revisions were made. Second, cognitive testing was performed with a group of seven conservation experts, who provided additional feedback to ensure that the questions were clear and contextually appropriate. Thus, the final version of the survey incorporated all suggested improvements.

The survey was launched on 4 March 2024 and remained open for four weeks, with a reminder email sent midway through the data collection period. A total of 8,299 valid invitation emails were sent to corresponding authors of articles published in 25 international journals on cultural heritage, resulting in 107 valid responses after outlier detection and quality control. Data were anonymized and processed in accordance with the General Data Protection Regulation [19]. Descriptive and inferential statistical analyses were performed to examine current practices, perceived barriers, and expectations regarding the future adoption of Industry 5.0. Likert scale responses were analyzed using measures of central tendency, and open-ended responses were interpreted using qualitative content analysis.

3 Results and Discussion

3.1 Findings from the Systematic Literature Review

The SLR process included 78 relevant studies from 872 records, with exclusions primarily due to irrelevance, lack of focus on Industry 5.0 principles or enabling technologies, and applicability outside the scope of BCH conservation. Following deduplication, the performance analysis on the remaining records revealed a steady increase in publications on Industry 5.0 from 2020 to 2023, with a projected rise in 2024, indicating a growing

interest in the AECMO&C industry. However, this growth is slower compared to other fields, such as sustainability [20], innovation [21], and manufacturing [22], likely due to the cautious adoption of new technologies in conservation, in line with the principles of the Venice Charter, which emphasize the careful testing and validation of materials and technologies used in cultural heritage interventions.

The science mapping analysis revealed four keyword clusters (see Fig. 1), with the most common terms related to cultural heritage and conservation, while environmental aspects formed separate groups. Key Industry 5.0 technologies like "artificial intelligence" and "digital twin" were linked to heritage preservation but remained isolated, highlighting gaps in research.

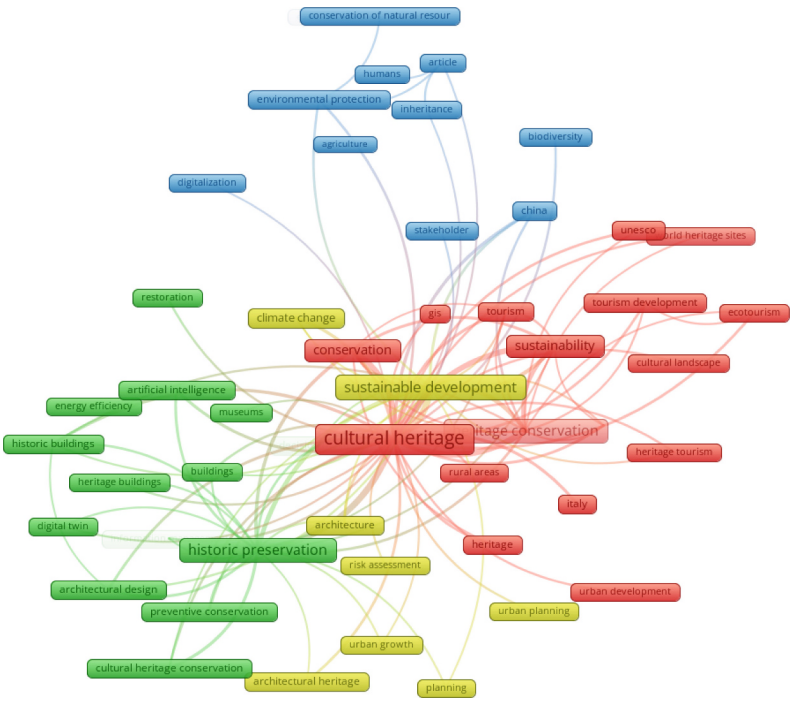

Fig. 1. Overall view of keywords co-occurrence map.

In terms of global representation, Italy leads the number of records, followed by Spain, the UK, and the US, with notable contributions from China and India. However, countries like Russia, Iran, Mexico, and France—despite having a significant number of UNESCO World Heritage Sites—show limited involvement. No countries from Latin America, Africa, or Southeast Asia are in the top ranks, highlighting the inequality gap between the Global North and Global South. Further research and local implementation of Industry 5.0 principles in the Global South could help address these imbalances [23]. The co-authorship map (see Fig. 2) also grouped countries into four clusters, with European nations leading the research output, while the Global South had limited but notable representation.

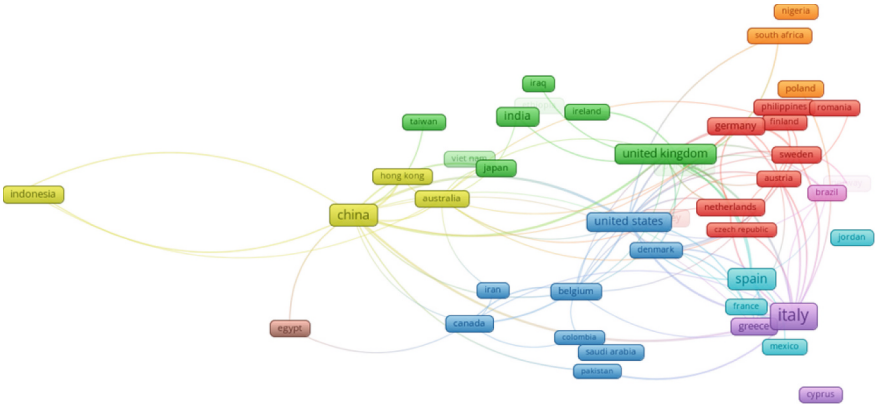

Fig. 2. Countries clustered into four different groups representing co-authorship relationships.

The 78 studies included in this SLR were analysed through narrative synthesis and categorized into two main groups: those dealing with Industry 5.0 principles, namely human-centrism (4 papers), resilience (5 papers), and sustainability (21 papers), and those discussing enabling technologies, with the most studied areas being DT (16 papers) and cyber-safe data transmission (16 papers), while other technologies like AI (7 papers), energy efficiency (4 papers), smart materials (2 papers), and human-machine interaction (3 papers) received comparatively less attention.

Human-centrism, reintroduced by Industry 5.0, has been examined through digital immersion, ethical AI frameworks, and participatory approaches, emphasizing a shift from material preservation to value-preservation practices, as demonstrated by Murphy et al. [24], Pansoni et al. [25], and Li et al. [26].

Resilience in BCH conservation is often attributed to long-surviving heritage assets, but Jones [27] critiques its vague and overused definition, calling for a stronger theoretical foundation and forward-looking approaches, while research efforts focus on mitigating both rapid- and slow-onset disasters through digital documentation, community-based recovery strategies, and smart reconstruction techniques supported by Industry 5.0 technologies.

Sustainability, the most extensively studied principle, has been explored covering social media as a tool for civic engagement and heritage awareness, sustainable tourism management to mitigate overtourism risks, and participatory conservation approaches that enhance community involvement and long-term preservation [28]. Circularity and adaptability are also key themes, with studies exploring economic models for assessing investment opportunities in heritage conservation [29], the environmental performance of historic buildings, and digital technologies supporting circular and adaptive reuse of cultural heritage models [30]. Additionally, sustainability-driven technological adoptions, such as cryogenics for non-invasive cleaning [31] and additive manufacturing for conservation modelling [32], are examined, along with frameworks and training programs aimed at equipping professionals with Industry 5.0-aligned skills [33].

Human-centric solutions in Industry 5.0 enhance, rather than replace, human capabilities through AI, augmented reality, and robotics. Nota and Petraglia [34] proposed a

cyber-physical decision support model for heritage buildings conservation, while Zhang et al. [35] introduced a BCH metaverse framework for cultural tourism, asset management and conservation. Salonia [36], who explored the role of robotics and augmented reality, among other digital technologies, highlighted challenges like high costs and process complexities, emphasizing the need for further research to facilitate Industry 5.0 adoption in BCH conservation.

DT link physical assets with virtual replicas for real-time monitoring. In BCH, the AI-HAIM [5] framework extends DT to BCH assets and includes interoperable data and health monitoring systems. Challenges in implementing DT include the lack of clear guidelines, database availability, and software interoperability. Advances in 3D modelling using drones and photogrammetry have improved accuracy in capturing asset geometry for DT. Several European case studies [37] have tested DT in BCH conservation, with more work needed to achieve fully functional DTs. Additionally, blockchain may aid DT authentication, while initiatives like VREA emphasize training to integrate digital technologies into conservation.

Industry 5.0 technologies like DT and AI generate vast, complex data, especially for large-scale BCH conservation projects. To manage this data, various digital platforms and information systems, like the INCEPTION [38] project and the Art-Risk 3.0 platform [39], have been developed. These platforms support data collection, processing, and collaboration, aiding decision-making in conservation. However, interoperability issues persist. Other platforms like SyPEAH and Europeana offer valuable resources for managing and disseminating cultural heritage data. Efforts are also underway to develop integrated digital systems for preventive conservation and improve data management strategies.

AI is widely used in BCH conservation, both as an independent tool and to enhance other digital technologies. Tzima et al. [40] used machine learning to analyse satellite data for heritage preservation in Cyprus. Alexakis et al. [41] applied deep learning to detect moisture damage, while Rodrigues et al. [42] employed convolutional neural networks for pathology detection and heritage building information modelling (HBIM) integration. More recently, Jiménez Rios et al. [43] implemented a machine learning framework estimate the annual corrosion rate of suspension bridge main cables and utilized Shapley Additive Explanations (SHAP) to explain the impact of each variable on the final modelling results.

To limit global warming to 1.5 °C, energy efficiency and trustworthy autonomy are crucial for achieving Net-Zero goals in CH conservation. Piselli et al. [44] reduced heating energy by 73% and CO_2 by 69% using HBIM-based retrofitting. Moyano et al. [45] utilized HBIM for energy parameter monitoring, and Massafra et al. [46] optimized thermal demand via simulation. Lucchi [47] reviewed photovoltaic integration, emphasizing aesthetic, technical, and energy criteria.

3.2 Findings from the Online Survey

A total of 8,299 invitation emails were sent. Out of the 6,577 successfully delivered emails, 115 responses were received, resulting in a 1.4% crude response rate and 1.7% adjusted response rate. The low participation was attributed to the voluntary online survey format.

The first part of the questionnaire aimed to explore current practices within the conservation professional community. Central tendency measurements (mode and median) were used to analyze Likert scale data, and the results for each question are summarized in Fig. 3. Questions 1 and 2 focused on the core principles of Industry 5.0, while Questions 3 and 4 addressed its enabling technologies. Question 5 assessed respondents' agreement with the benefits of Industry 5.0 adoption as outlined by the European Union. Finally, Questions 6 and 7 explored future practices and respondents' views on preparation measures and anticipated impacts. Respondents could choose from predefined options or select "other" to provide additional insights.

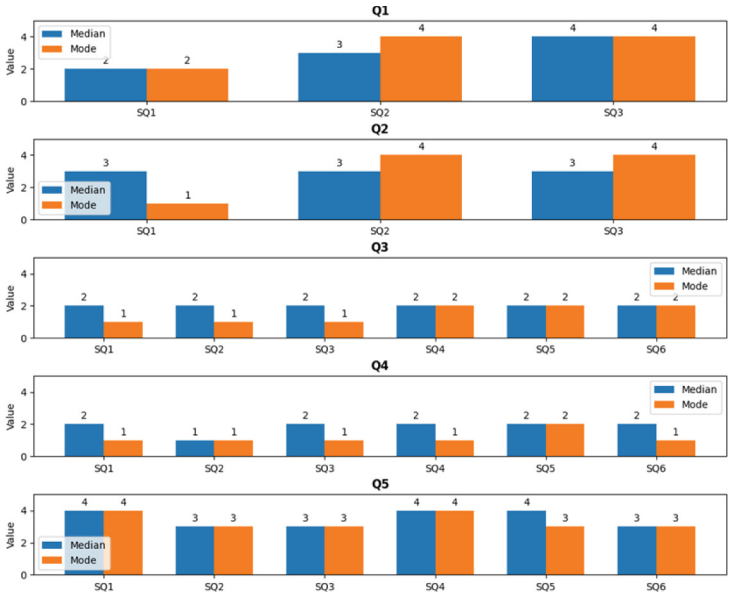

Fig. 3. Measurements of central tendency for Questions 1 to 5 (*Q* refers to the main question number; *SQ* indicates the corresponding sub-question).

The third part of the questionnaire focused on barriers to adopting Industry 5.0 in BCH conservation and the skills needed to address these challenges. Question 8 was open-ended, allowing respondents to share their views, with the responses qualitatively analyzed and presented as a word cloud in Fig. 4. Question 9 assessed respondents' views on key skills identified by the World Manufacturing Forum as crucial for the future. Respondents rated the utility of each skill in overcoming the barriers mentioned in Question 8. The mean and mode of responses for each skill are summarized in Fig. 5.

The fourth part of the survey focused on demographic questions to characterize the respondent group. These questions, adapted from similar surveys in the cultural heritage sector [48], collected information on the type of cultural heritage institution respondents are employed at, its size and location, the type of cultural heritage asset it manages, and respondents' roles within their organizations. The collected demographic data is presented in Fig. 6 as a series of treemap charts.



Fig. 4. Word cloud presenting the barriers perceived by BCH conservation professionals to the adoption of industry 5.0 principles and enabling technologies.

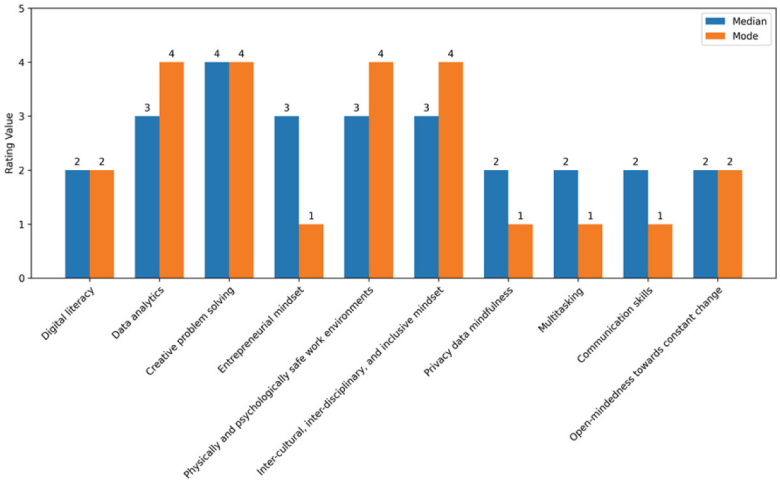

Fig. 5. Medians and modes for Question 9: How can these barriers be overcome?

The survey results align with the finding of the SLR, showing that the built cultural heritage conservation community mainly focuses on sustainability within Industry 5.0 principles. Respondents were more familiar with sustainability, followed by resilience, and had limited knowledge of human-centrism. While sustainability and resilience are moderately adopted in respondents' workplaces, human-centrism remains largely unintegrated. Engagement with Industry 5.0 enabling technologies was low, with respondents only slightly familiar with them and reporting minimal adoption in their work.

Respondents expressed neutral to slightly positive views on the potential benefits of Industry 5.0, particularly regarding cost reduction and skills adaptation. Over 80% suggested improved education and training as key for adopting Industry 5.0, followed by increased investment in research and development. Adoption could enhance cultural

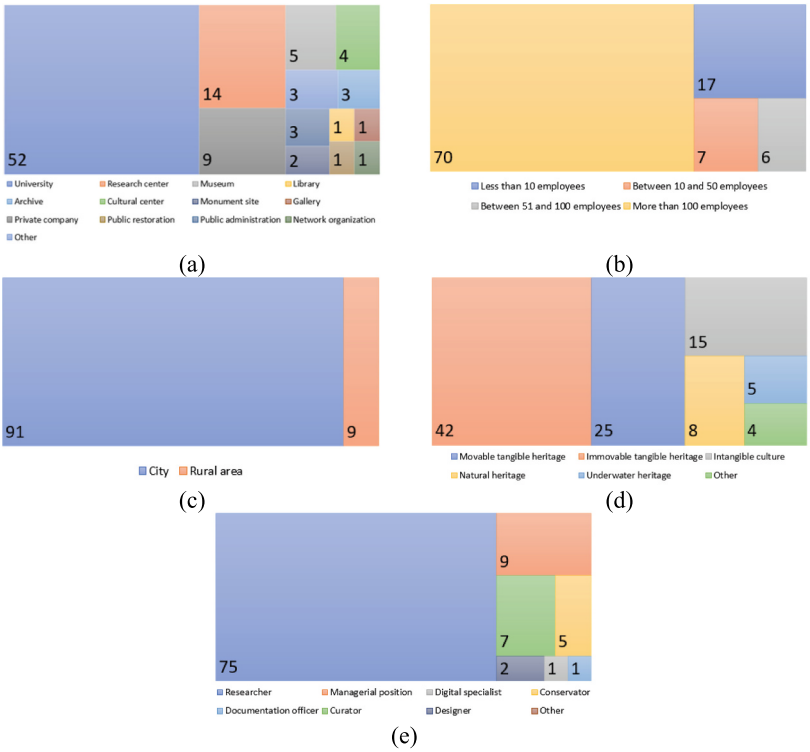

Fig. 6. Survey's questions related to the demographic characteristics of respondents: (a) In which type of cultural heritage institution do you work? (b) How big is it? (c) Where is it located? (d) What type of cultural heritage do you work with? (e) Which of the following options better defines your position in the field of cultural heritage?

heritage documentation and preservation, but 35% of respondents cautioned against the early use of untested technologies.

Barriers to adoption include a lack of knowledge, insufficient training, and limited resources. Skills in data analytics, creative problem-solving, and an inclusive mindset are needed to overcome these challenges. Most respondents work in universities or research centres, with a focus on immovable tangible heritage. The findings highlight a need for better collaboration among researchers, managers, and designers to integrate Industry 5.0 in practice.

To strengthen the integration of Industry 5.0 in heritage conservation, the study suggests aligning policy initiatives with conservation practitioners' needs, supporting skill development, access to technologies, and fostering interdisciplinary collaboration. Targeted funding for pilot projects and specialized training programs could facilitate a smoother transition.

While the study offers valuable insights, certain limitations should be considered. The device used by respondents was not recorded, and completing the survey on smaller screens, such as smartphones, may have extended completion time and affected response

rates. The low adjusted response rate may be partly due to the online format and the absence of incentives for participation. Additionally, no non-respondent analysis was conducted due to time and budget constraints, though comparisons between early and late respondents showed no significant differences. Finally, the survey reflects participants' perceptions at a specific point in time, and future longitudinal studies could provide a better comparative view of Industry 5.0 adoption.

4 Conclusions

The integration of Industry 5.0 principles and enabling technologies into BCH conservation presents a transformative opportunity to enhance preservation practices in a more sustainable, resilient, and human-centric way. This study, drawing from both a SLR and an online survey, has provided valuable insights into the current state of technological adoption in the field, highlighting both opportunities and challenges associated with this transition.

The findings from the SLR indicate that emerging technologies such as AI, DT, and XR have already begun reshaping documentation, assessment, and intervention strategies for heritage conservation. However, the literature also underscores a critical gap in the comprehensive application of Industry 5.0 principles, particularly in achieving true human-centrism, fostering interdisciplinary collaboration, and ensuring sustainable conservation practices. While technological advancements have improved efficiency and precision in heritage conservation, the review suggests that ethical considerations, skills development, and knowledge-sharing frameworks remain underexplored.

The online survey results reinforce several of these observations but also bring forward additional practical barriers encountered by conservation professionals. Survey respondents acknowledged the potential benefits of Industry 5.0 technologies but expressed concerns regarding limited access to funding, the high cost of implementation, and the lack of specialized training. Moreover, while many respondents recognized the importance of sustainability and resilience in conservation, they highlighted a need for clearer guidelines and policies to facilitate the integration of these principles into their daily practice. It is worth noting though that the low survey response rate obtained slightly weakens the representativeness of the practitioner insights.

One key area where both sources align is the recognition that human expertise and traditional craftsmanship must remain at the core of conservation efforts. While advanced technologies offer powerful tools for documentation and intervention, they should be used to support rather than replace the knowledge and skills of conservation professionals. This balance is crucial for ensuring ethical and context-sensitive heritage preservation of BCH.

In conclusion, while Industry 5.0 offers a promising pathway for advancing BCH conservation, its successful integration needs a holistic strategy that considers technological, economic, and socio-cultural dimensions. By addressing the identified barriers and fostering a collaborative ecosystem, the heritage sector can harness the full potential of these innovations to ensure the long-term preservation and accessibility of cultural assets for future generations.

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