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Towards Enhanced Built Cultural Heritage Conservation Practices: Perceptions on Industry 5.0 Principles and Enabling Technologies

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ABSTRACT

Despite its recent adoption, Industry 5.0 has attracted significant attention from researchers across various fields. However, the Architecture, Engineering, Construction, Management, Operation, and Conservation (AECMO&C) industry, particularly in the context of built cultural heritage conservation, has lagged in this regard. This study aims to gain a deeper understanding of conservation professionals' perceptions regarding the adoption of Industry 5.0 principles and enabling technologies, as well as the perceived barriers and the skills needed to address them. A survey questionnaire was designed, tested, and implemented to collect relevant data. Analysis of the collected data reveals that, although there is a clear recognition of the significance of Industry 5.0 principles and enabling technologies, their application in built cultural heritage conservation remains limited. Future initiatives should prioritise bridging knowledge gaps, enhancing training programmes, and securing necessary resources to overcome these existing barriers.

KEYWORDS

Industry 5.0; human-centrism; resilience; sustainability; built cultural heritage environment; conservation

Introduction

An 'industrial revolution' refers to a series of significant technological advancements that have led to paradigm shifts, profoundly influencing societies living conditions. Historically, three industrial revolutions have been defined ex-post: 1st Industrial Revolution, characterised by the mechanisation of industry through water and stem power; 2nd Industrial Revolution, marked by the transition to electrical power and the emergence of production lines facilitating mass production; 3rd Industrial Revolution,

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defined by the introduction of computers and electronics, which enabled the automation of repetitive tasks (see Figure 1).

In contrast, Industry 4.0 and Industry 5.0 have been defined ex-ante, based on the anticipated impact of emerging technologies[1] (see Figure 1). Industry 4.0 envisioned increased digitisation of human activities, driven by technologies such as the Internet of Things (IoT), cyber-physical systems, information and communications technologies, and enterprise architecture and integration[2]. The European Union has introduced a new vision: Industry 5.0. Rather than replacing Industry 4.0, this paradigm builds upon it, emphasising sustainability, resilience, and a human-centred approach[3]. Its objectives include reducing costs, empowering workers, improving training for evolving skills, gaining a competitive edge in emerging markets, and enhancing safety and well-being[4]. Key enabling technologies of Industry 5.0 encompass human-machine interaction, bio-inspired materials, digital twins, artificial intelligence, and energy-efficient systems[5].

Recent advancements in Industry 4.0 have positively impacted cultural heritage conservation[6]. For instance, extended reality has enhanced visitor experiences in museums[7], virtual reality models have facilitated a better understanding of urban cultural heritage[8], and the integration of building information modelling with IoT technologies has improved museum and site management[9]. Additionally, digital twins are being utilised to preserve museum collections[10] and to optimise the management of historic bridges[11,12,13]. While Industry 4.0 has increased productivity and digitalisation within cultural heritage conservation[14,15,16], it has also raised concerns regarding environmental impacts and fears that automation may threaten jobs. Consequently, Industry 4.0 has been criticised for falling short of sustainability goals and inadequately addressing social inequalities and climate change[17].

Although relatively new, Industry 5.0 has already attracted considerable interest, with researchers investigating its core principles and technologies,[18,19,20]and proposing innovative implementation strategies[21,22,23]. Applications in fields such as manufacturing[24], education[25], data privacy[26], and wind energy[27] have already been explored. However, the Architecture, Engineering, Construction, Management, Operation, and Conservation (AECMO&C) industry, particularly in the context of built cultural heritage conservation, has not kept pace. Proactive steps are necessary to successfully adopt Industry 5.0 principles and enabling technologies.

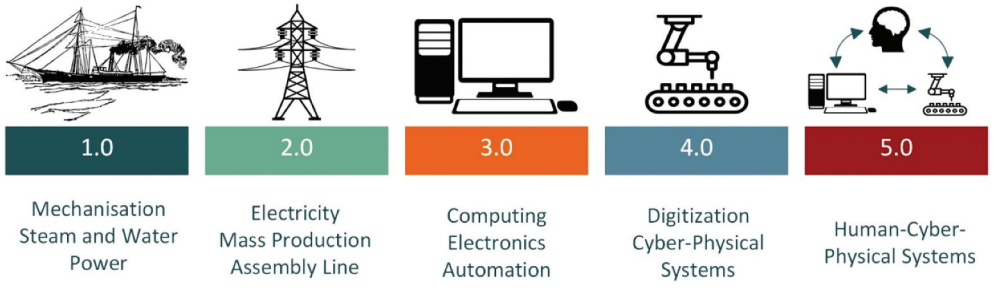

Figure 1. Industrial revolutions.

Manuscript Description and Content

The aim of this study is to enhance our understanding of how conservation professionals perceive the adoption of Industry 5.0 principles and enabling technologies. In this context, built cultural heritage encompasses man-made structures, buildings, landmarks, and spaces with historical, architectural, artistic, cultural, or social importance. The United Nations (UN) has acknowledged in its Sustainable Development Goals (SDG) that safeguarding cultural heritage is essential for creating more inclusive, safe, resilient, and sustainable cities and human settlements[28]. It is now widely accepted that preserving the built cultural heritage environment is both necessary and desirable[29]. Therefore, this study seeks to examine current practices, explore potential future benefits, and identify the barriers and skills required to overcome these challenges. Ultimately, this research aims to facilitate the successful adoption of Industry 5.0, enabling its transformative benefits to be fully realised.

Materials and Methods

This section outlines the design, testing, and implementation of the survey questionnaire, as well as the data analysis process. The overall methodology is depicted in Figure 2, and the full questionnaire is included in Appendix A.

Questionnaire Design

The survey was an exploratory cross-sectional study[30] aimed at understanding how stakeholders in built cultural heritage conservation perceive Industry 5.0 principles and enabling technologies. Participants were surveyed once about their experiences with this transformative vision promoted by the European Union. The structured questionnaire used a mix of question types, including single choice (Likert scale[31]), multiple choice, and open-ended question. This variety was chosen to gather meaningful information across different topics, avoid respondent monotony and boredom, and prevent common method bias[32] and satisficing behaviour (choosing the easiest option without proper consideration).

As the survey was self-administered online, the most engaging questions were placed at the beginning to capture participant's attention, while demographic questions were saved for the end. All questions were mandatory to minimise missing data and incomplete submissions. The questionnaire form was created using Nettskjema (https://nettskjema.no/), a web-based tool from University of Oslo, Norway, that automatically storage data and provides summary reports. The data was coded to simplify the analysis process.

Questionnaire Testing

The first version of the questionnaire was created by the first author of this article. During the initial testing phase, two co-authors reviewed it and suggested minor changes to enhance its clarity and quality. At this stage, skip routines were also tested and validated. In the second step, cognitive testing was conducted. The goal was to ensure that the questions would generate accurate, meaningful, and comparable data from respondents,

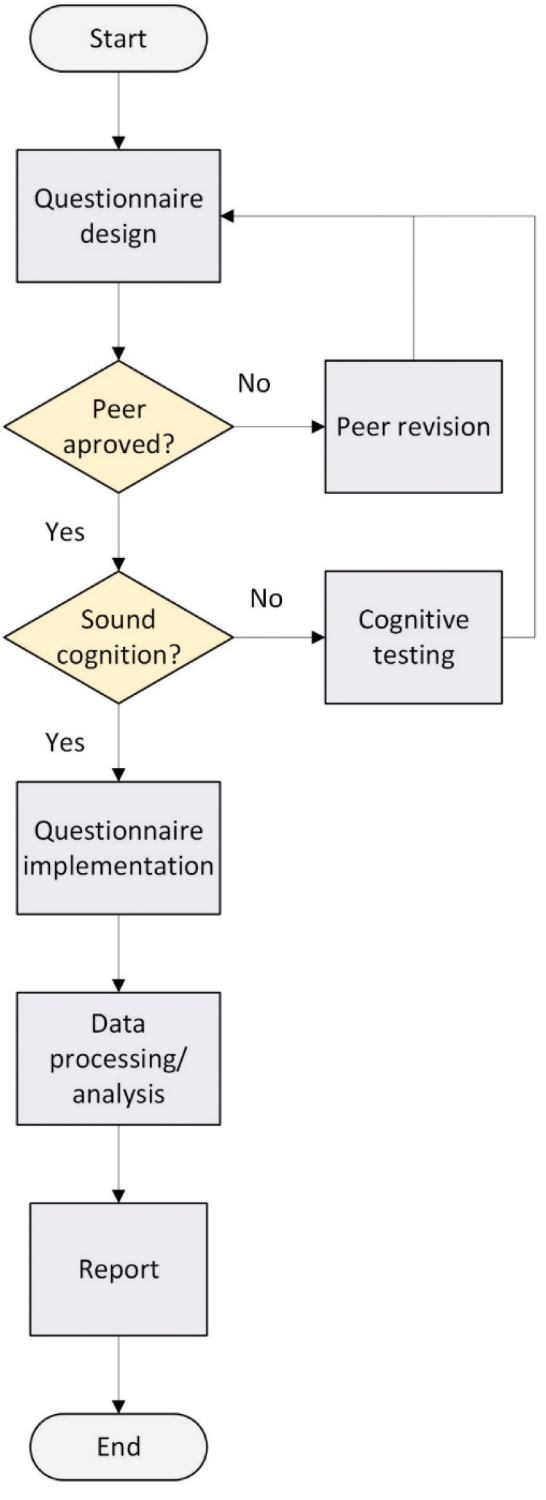

Figure 2. Overall methodology followed to conduct the survey.

while also evaluating the questionnaire's structure, completion time, and language. This phase involved seven experts in built cultural heritage conservation, including the two remaining co-authors.

Based on the feedback received from these group of respondents, the questionnaire was further improved with minor revisions before it was finally distributed to the final participants. A pilot survey was not conducted due to time and budget constraints, as well as challenges in obtaining sufficient responses through an online-only approach. Although a pilot is often recommended, it was not considered mandatory in this case.

Questionnaire Implementation

The survey was conducted online using the Nettskjema tool, chosen for its low cost, fast delivery, and automatic data collection. The online application also presents advantages in terms of improved data quality by flagging unanswered questions and using automated filter instructions to reduce respondents' burden. Respondents could access the survey by clicking a link or scanning a QR code using either a desktop, tablet, or mobile phone. Every respondent was allowed to answer the survey only once. An invitation email with key details, including the access link and QR code, was sent on 4 March 2024 (Monday). The survey remained opened for four weeks, with a reminder email sent on March 25 (Monday). The survey closed on March 31 (Sunday), and all responses were saved in a.csv file. Unfortunately, the survey did not capture data on the type of device used by respondents. Making all questions mandatory ensured complete responses, although this may have affected the response rate, as incomplete attempts were not recorded.

The target audience for the survey included experts and stakeholders in built cultural heritage conservation. On 9 February 2024, corresponding authors from 25 cultural heritage journals were identified using Scopus, resulting in 18,478 entries (see Table 1). After cleaning the data (removing duplicates and missing information), a final sample of 8,311 subjects was compiled. Although the exact number of cultural heritage conservators worldwide is unknown, targeting experts who have published in international journals ensures a relatively global sample. Researchers from diverse countries contribute to these journals, enhancing the representativeness of the survey across various geographies. Thus, the sample, though not fully comprehensive, includes a substantial cross-section of individuals involved in the field globally and represents a useful dataset. Given the anticipated low response rate, a census method was adopted to invite all these subjects to participate.

The survey was conducted in English as all participants had previously published research in international journals, implying a good level of English proficiency. Response times were recorded (paradata) and used to identify satisficing behaviour and remove speeders. As the survey was fully anonymised, the breach of any ethical issues related to personal data was avoided in compliance with General Data Protection Regulations (GDPR)[33]. Participation was voluntary, and consent was implied by the act of completing the survey.

Table 1. Number of records found in different journals in the field of conservation.

Journal	Papers found
Conservation and Management of Archaeological Sites	281
Historic Environment: policy and Practice	267
International Journal of Architectural Heritage	1156
International Journal of Heritage Studies	1306
Journal of Architectural Conservation	486
Journal of Paper Conservation	0
Journal of the Institute of Conservation	263
Journal of Field Archaeology	1638
Journal of Heritage Tourism	550
Studies in Conservation	3012
Museum International	2307
Journal of Community Archaeology and Heritage	231
International Journal for the Preservation of Library and Archival Material	781
Restoration of Building and Monuments	0
Preservation, Digital Technology, and Culture	206
Curator: The Museums Journal	462
Journal of Cultural Heritage Management and Sustainable Development	461
Journal of Heritage Management	0
Journal of Cultural Heritage	3028
Digital Applications in Archaeological Cultural Heritage	262
Architectural Histories	139
Engineering History and Heritage	0
Ge-conservación	446
Journal of the American Institute for Conservation	0
Heritage	1196
Total	**18478**

Data Processing

Response rates were calculated in two ways: one based on the total number of invitation emails sent (crude response), and the other based on the number of emails that were successfully delivered (adjusted response). The survey was completely anonymous, so no tracking data was collected for individual respondents, although response dates were recorded to observe any differences between early and late respondents.

The first stage of data processing involved removing extreme outliers and speeders. Outliers were identified using a box plot, with extreme outliers defined as points more than three times the interquartile range from the box edge[34], being removed. Responses completed in less than one-third of the average completion time were excluded. The questionnaire was manually coded before distribution. Likert items were analysed by computing their mode, median, and by visualising responses with bar charts. Open-ended responses (question 8) were analysed and interpreted through a words map. Finally, the demographics data was studied with pie charts.

Results

On 9 February 2024, bibliographic data from 18,478 records were identified in Scopus (see Table 1). Following data cleaning and deduplication, 8,311 records remained, including 12 unrecognisable emails, resulting in 8,299 valid invitation emails. Of these, 6,577 were successfully delivered. By the time the survey was closed, 115 responses had been received, yielding a crude response rate of 1.4% and an adjusted response rate of 1.7%. This low response rate can primarily be attributed to the online survey format and its fully voluntary nature. Budget and

time constraints prevented the team from conducting a non-respondent analysis. To mitigate potential response bias, we compared early and late respondents, assuming late respondents would resemble non-respondents in their answers[35]. The absence of significant differences between early and late responses supports the validity and utility of the survey results.

As the survey was fully anonymised, no personal data were collected, processed, or stored, eliminating any ethical concerns and the need for further anonymisation. This work was funded by the European Union, and the raw data collected have been made publicly available, see[36], in compliance with open science policies.

The frequency of survey submissions is presented in Figure 3. The majority of responses (56) were received on the first day. An additional 32 responses followed within the first week (March 5–10). Response rates significantly declined in the second and third weeks, with only 8 submissions. A slight increase occurred in the first two days of the final week, following the reminder email, with no further responses in the last two days.

Survey completion times were first converted to minutes, with interquartile (IQ) values recorded as IQ1 = 5.43, IQ2 = 8.03, IQ3 = 11.31 minutes, resulting in an interquartile range (IQR) of 5.88 (see Figure 4). This established a threshold of 28.95 minutes for identifying extreme outliers, leading to the exclusion of five responses. The average completion time for the remaining 110 responses was 9 minutes. Responses completed in less than one-third of this average time were labelled as 'speeders,' indicating potential satisficing behaviour. Three responses were thus removed, leaving 107 valid responses for analysis.

Most of the common errors committed while respondents answer questionnaires (i.e. illogical or ineligible responses, incomplete responses, etc.) were avoided by using an online format. Moreover, missing values were minimised by making every question compulsory for the completion of the survey. Nevertheless, certain responses in Question 8 (see Appendix A) may be considered as missing, including entries like '-', "/",'?', 'n/a', 'x', 'not sure', 'I need more information', 'I have no idea' as these do not correspond to what could be considered a barrier for Industry 5.0 adoption. On the other hand, 'none' was considered a valid response, indicating that the respondent perceived no barriers. Eighteen responses were 'missing', representing 16.8% of the total. Given the open-ended nature of this question, response variability was substantial, with some respondents listing only one barrier and others several. Due to this diversity, and the limitations inherent in an open-text format, it was considered unnecessary (and unfeasible) to apply any imputation method to fill up the missing values.

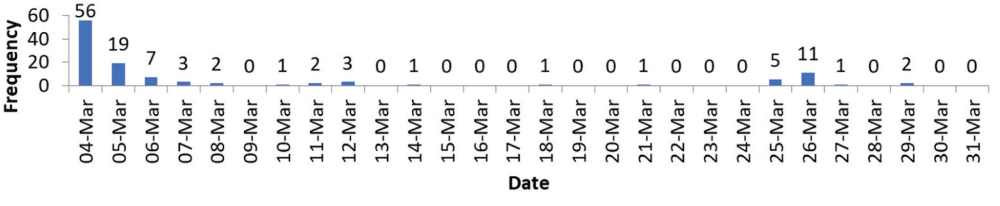

Figure 3. Response frequency. Survey started on 04/03/2024 and was closed on 31/03/2024.

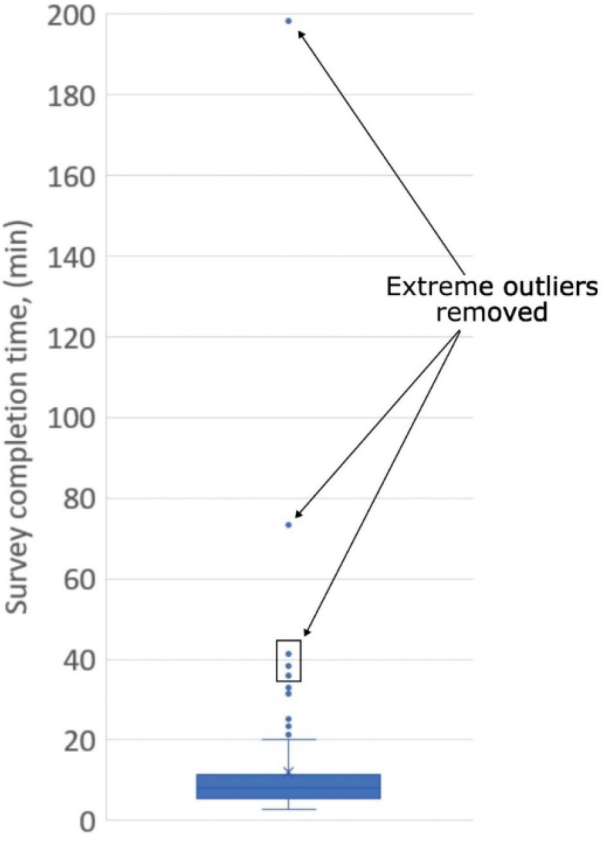

Figure 4. Detection and removal of extreme outliers based on survey completion time (min).

Current Practices

In the first part of the questionnaire, we aimed at illuminating current practices within the conservation professional community. Table 2 presents the central tendency measurements, mode and median, suitable for analysing Likert scale data[37] for each question on this part of the questionnaire. Questions 1 and 2 addressed the core principles of Industry 5.0, while Questions 3 and 4 focused on its enabling technologies. Additionally, Question 5 gauged respondents' agreement with the benefits of Industry 5.0 adoption as outlined by the European Union.

Figure 5(a-c) show respondents' familiarity with the principles of human-centrism, resilience, and sustainability, respectively. Figure 6 presents the extent to which these principles are currently adopted in respondents' work practices. Similarly, Figures 7 and 8 display respondents' familiarity with and degree of implementation of Industry 5.0 enabling technologies. Finally, Figure 9 demonstrates respondents' agreement regarding the expected benefits of successfully adopting Industry 5.0. Figure 9(a) is related to costs reduction through resource efficiency, (b) to workers' empowerment by allowing them having greater control, (c) to an enhance industry

Table 2. Measurements of central tendency for the replies to the questions related to current practices of the questionnaire.

Question	Sub question	Median	Mode
Q1	SQ1	2	2
	SQ2	3	4
	SQ3	4	4
Q2	SQ1	3	1
	SQ2	3	4
	SQ3	3	4
Q3	SQ1	2	1
	SQ2	2	1
	SQ3	2	1
	SQ4	2	2
	SQ5	2	2
	SQ6	2	2
Q4	SQ1	2	1
	SQ2	1	1
	SQ3	2	1
	SQ4	2	1
	SQ5	2	2
	SQ6	2	1
Q5	SQ1	4	4
	SQ2	3	3
	SQ3	3	3
	SQ4	4	4
	SQ5	4	3
	SQ6	3	3

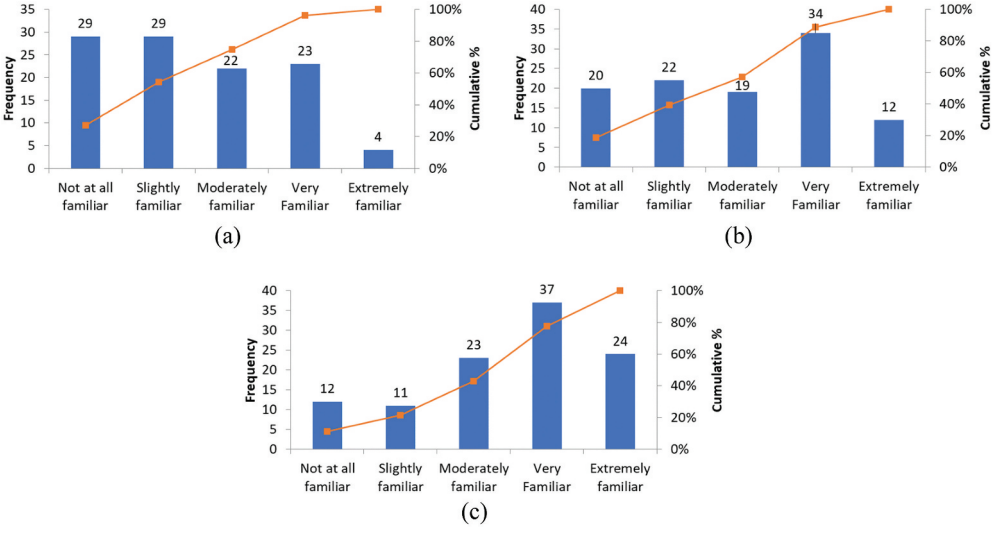

Figure 5. Question 1: How familiar are you with the industry 5.0 principles? (a) Human-centrism, (b) Resilience, and (c) Sustainability.

competitiveness by attracting top talent, (d) to training programmes adaptations to evolving skills, (e) to the competitive advantage given in new markets, and (f) to the improved safety and well-being.

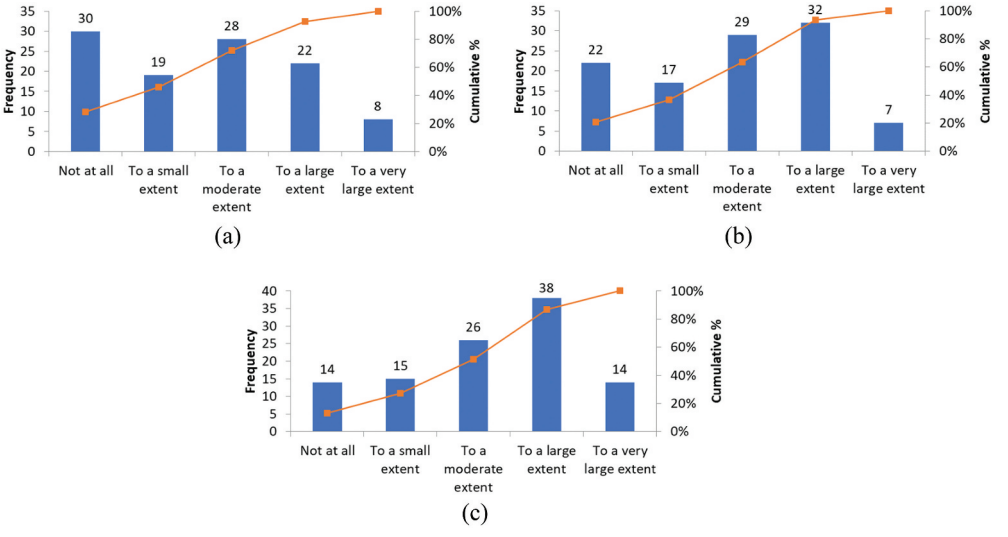

Figure 6. Question 2: to what extent are the industry 5.0 principles currently incorporated into your work? (a) Human-centrism, (b) Resilience, and (c) Sustainability.

Future Practices and Opportunities

Questions 6 and 7 explored future practice perspectives, as well as respondents' views on preparation measures and anticipated impacts. In addition to a series of predefined answer options, respondents were given the opportunity of selecting the 'other' option and provide additional insights in text.

Figure 10 shows the percentage of respondents selecting different proposed preparation strategies; with multiple selections allowed. Figure 11 highlights respondents' perceptions of the potential impacts that adopting this novel paradigm could have on built cultural heritage conservation.

Barriers

The third part of the questionnaire focused on the anticipated barriers for the adoption of Industry 5.0 within built cultural heritage conservation, as well as the skills potentially needed to address these challenges. Question 8 was an open-ended question, allowing respondents to express their views in free text. These responses were qualitatively analysed and are visually represented as a word cloud in Figure 12.

Question 9, in contrast, assessed respondents' views on a series of key skills identified by the World Manufacturing Forum as the top ten skills for the future[38]. Respondents rated the perceived utility of each skill in overcoming the barriers mentioned in Question 8. Figure 13 displays these ratings in a stacked bar plot, with respondents assigning a usefulness score ranging from 0 (not useful at all) to 5 (very useful) for each skill. The mean and mode of responses for each skill are summarised in Table 3.

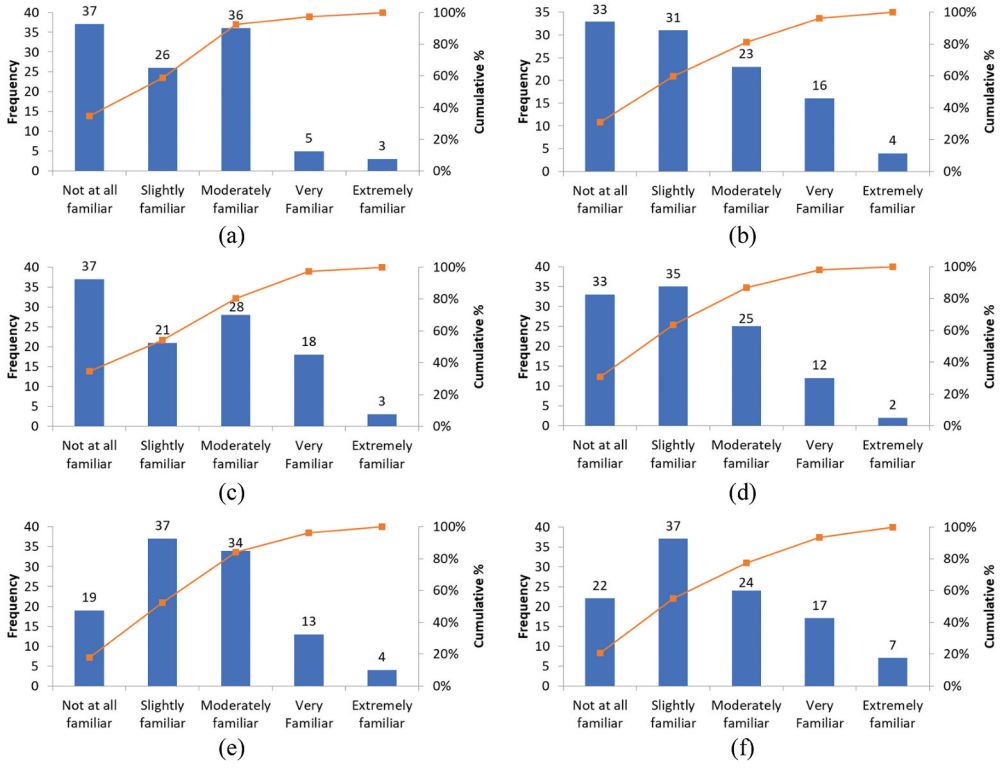

Figure 7. Question 3: How familiar are you with the enabling technologies? (a) Human-centric solutions and human-machine interaction, (b) Bio-inspired technologies and smart materials, (c) Real time-based digital twins and simulation, (d) Cyber safe data transmission, storage, and analysis, (e) Artificial intelligence, and (f) Energy efficiency and trustworthy autonomy.

Demographics

The fourth and final part of the survey consisted of demographic questions aimed at characterising the respondent group. These questions were adapted from similar surveys in the cultural heritage sector[39] to capture relevant information on the type of cultural heritage institution where respondents are employed, the institution's size and location, the type of cultural heritage asset it manages, and respondents' roles within their organisations. The demographic data collected is presented in Figure 14 as a series of pie charts.

Discussion

Jiménez Rios et al. [40] noted that within the three core principles of Industry 5.0, the built cultural heritage conservation community has primarily concentrated on sustainability. This observation aligns with our survey results, as shown in Question 1, which reflects the personal familiarity levels of respondents with each principle. While most respondents reported being very or extremely familiar with sustainability ($Q1\_SQ1_{median} = 4$), they were only moderately familiar with resilience ($Q1\_SQ2_{median} = 3$) and generally reported limited

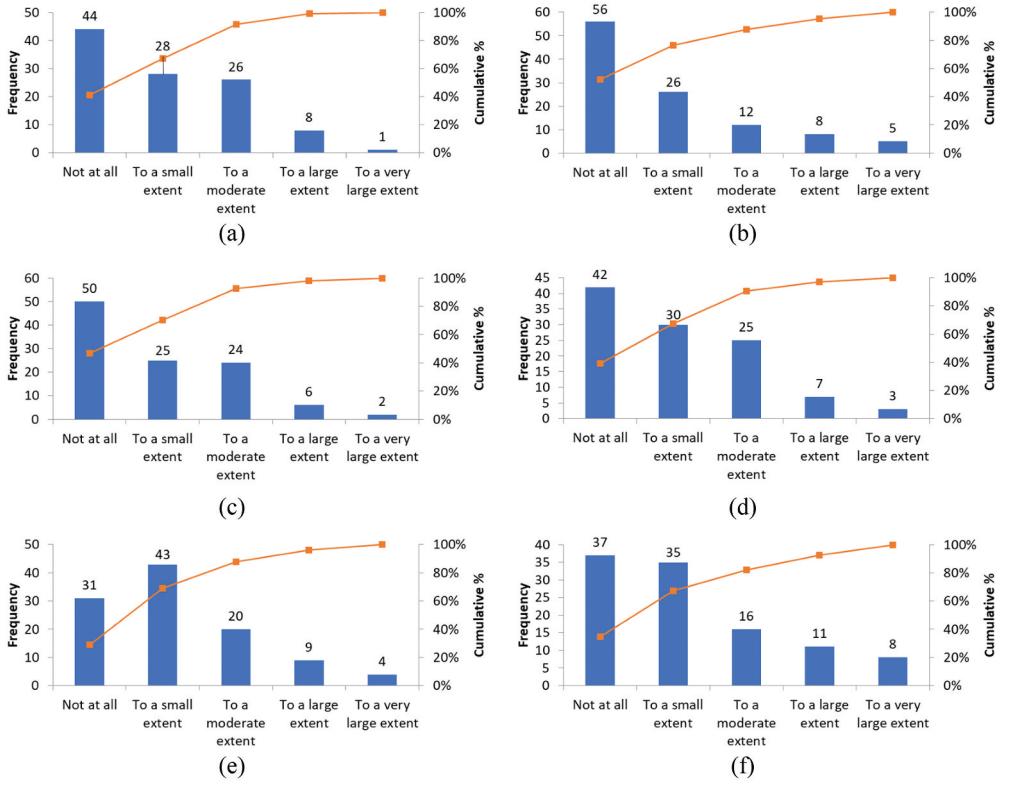

Figure 8. Question 4: To what extent are these enabling technologies currently incorporated into your work? (a) Human-centric solutions and human-machine interaction, (b) Bio-inspired technologies and smart materials, (c) Real time-based digital twins and simulation, (d) Cyber safe data transmission, storage, and analysis, (e) Artificial intelligence, and (f) Energy efficiency and trustworthy autonomy.

familiarity with human-centrism ($Q1\_SQ3_{median} = 2$). In contrast, Question 2 offers insights into institutional practices, as respondents rated the degree to which their workplace adopt these principles, likely influenced by organisational policies. Here, all principes show moderate incorporation ($Q2\_SQ1, 2, 3_{median} = 3$). However, sustainability and resilience are recognised as substantially embedded ($Q2\_SQ2, 3_{mode} = 4$), while human-centrism appears largely unintegrated in most respondents' work environments ($Q2\_SQ1_{mode} = 1$).

In contrast, personal and institutional engagement with Industry 5.0 enabling technologies appear consistently low. According to responses to Question 3, most respondents are only slightly familiar with all enabling technologies ($Q3\_SQ1, 2, 3, 4, 5, 6_{median} = 2$). Notably, they recognised that all enabling technologies had been incorporated into their work only to a small extent ($Q4\_SQ1, 3, 4, 5, 6_{median} = 2$), with the exception of bio-inspired technologies and smart materials, which remain largely unadopted ($Q4\_SQ2_{median} = 1$). This underscores an urgent need to drive the implementation of novel technologies in cultural heritage conservation, a process currently hindered by global inequalities, the conservative approach adopted in conservation charters[41], and the need to rigorously validate new materials on conservation applications.

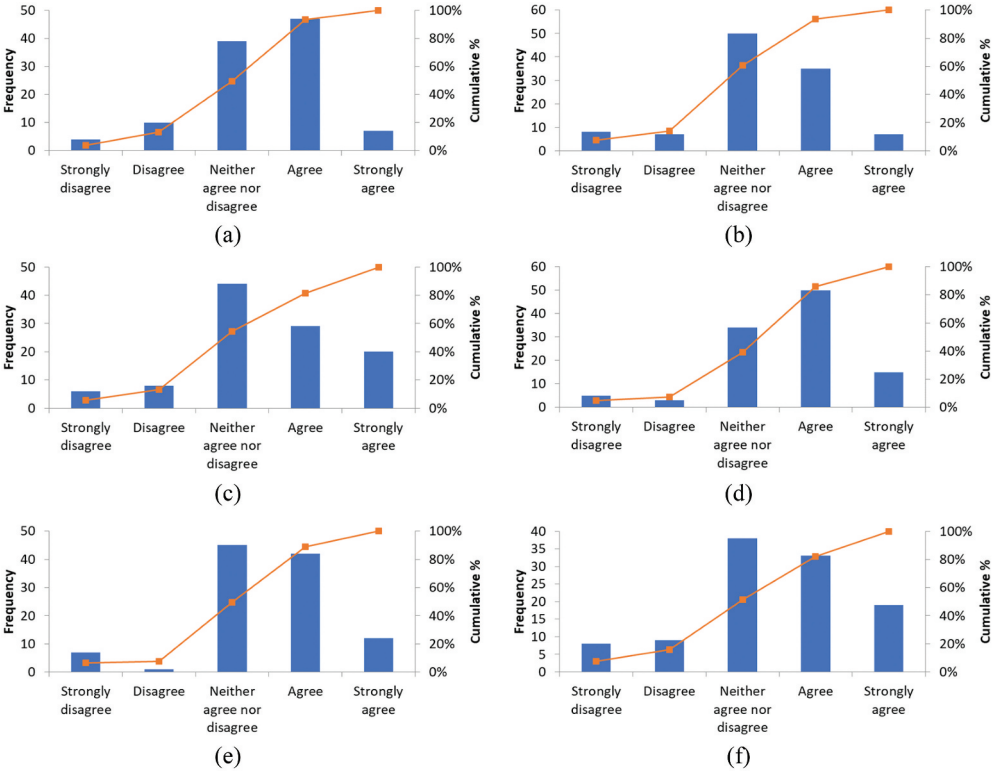

Figure 9. Question 5: How strongly do you agree/disagree with the following statements: "industry 5.0 will . . . (a) Reduce cost due to resource efficiency, (b) Empower workers by allowing them to remain in control, (c) Create a competitive industry by attracting the best talent, (d) Enhance adaptation by providing training for evolving skills, (e) Give a competitive edge in new markets, and (f) Improve safety and wellbeing.

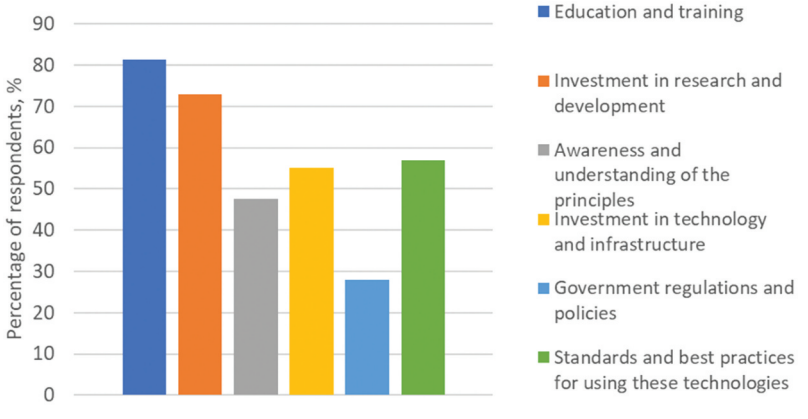

Figure 10. Question 6: How do you think the architecture, engineering, construction, management, operation, and conservation (AECMO&C) industry can better prepare to embrace industry 5.0 principles and enabling technologies?

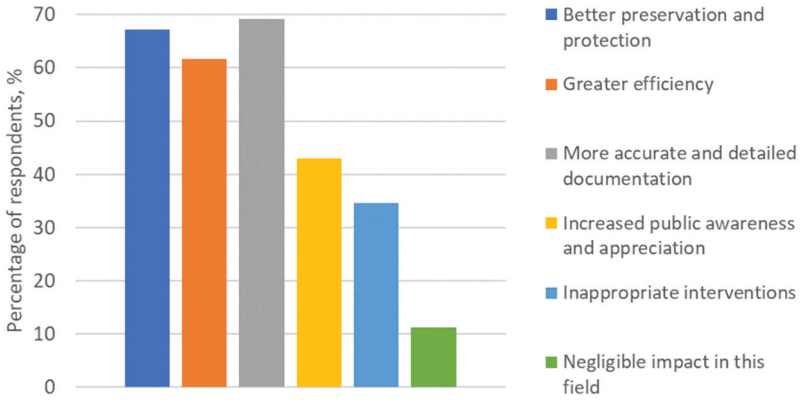

Figure 11. Question 7: What potential impacts do you foresee these changes would have on the conservation of built cultural heritage?

Figure 12. Question 8: What do you perceive as the main barriers to the adoption of industry 5.0 principles and enabling technologies in your work?

Regarding the perceived benefits of Industry 5.0 principles and enabling technologies (see Figure 9), respondents generally expressed neutral or slightly positive views. Although most respondents felt Industry 5.0 might not notably empower workers, attract top talent, enhance competitiveness in new markets, or improve safety and wellbeing ($Q5\_SQ2, 3, 5, 6_{mode} = 3$), a majority agreed that it could reduce costs through efficiency and support skills adaptation via training ($Q5\_SQ1, 4_{mode} = 4$). These insights can guide resource allocation to foster the necessary changes for a successful transition to this innovative paradigm.

A path forward was also suggested through Question 6, where respondents identified measures for the AECMO&C industry to adopt Industry 5.0 principles and enabling technologies. Over 80 % of respondents highlighted improved education and training, along with increased investment in research and development (73 %), as essential steps. Additional recommendations included community engagement, practitioners' involvement in policy-making, and raising public awareness. Investment in technology and

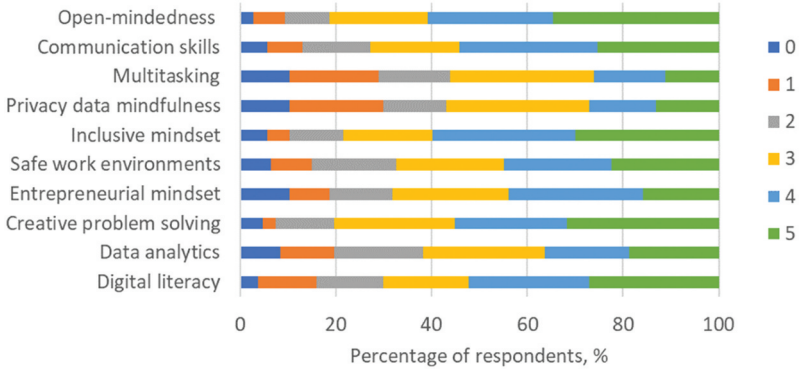

Figure 13. Answers to question 9: How can these barriers be overcome? (the indicated skills were ranked based on how helpful respondent thought they could be used to overcome the barriers they perceived, being 5 as very helpful and 0 as not helpful at all).

Table 3. Measurements of central tendency for the replies to question 9: How can these barriers be overcome?

Question	Skill	Median	Mode
Q9	Digital literacy	2	2
	Data analytics	3	4
	Creative problem solving	4	4
	Entrepreneurial mindset	3	1
	Physically and psychologically safe work environments	3	4
	Inter-cultural, inter-disciplinary, and inclusive mindset	3	4
	Privacy data mindfulness	2	1
	Multitasking	2	1
	Communication skills	2	1
	Open-mindedness towards constant change	2	2

infrastructure, as well as the development of standards and best practices, were also supported by 55 % and 57 % of respondents, respectively. If these measures are implemented, respondents anticipated more accurate and detailed documentation of cultural heritage (69 %), better preservation and protection of cultural heritage (67 %), and greater efficiency in conservation efforts (62 %). This is a key insight because it highlights the transformative potential of Industry 5.0 in cultural heritage management, particularly in enhancing the documentation, preservation, and conservation of heritage assets.

Despite the generally optimistic responses, 35 % of respondents cautioned that early adoption of untested technologies could lead to inappropriate interventions. Such scenarios have occurred in the past, such as the misapplications of reinforced concrete following the Athens Charter[42], underscoring the importance of prudence in technology adoption to prevent inadequate conservation practices.

The adoption of Industry 5.0 principles represents an 'untamed' problem, as described by van de Graaf and Hoppe[43], requiring extensive social consensus and confronting substantial technological uncertainty. Addressing this challenge demands a multi-actor engagement and agreement[44]. Commonly cited barriers to adoption of Industry 5.0 (see Figure 12) include the lack of knowledge about the principles, insufficient training to handle its enabling technologies, and limited funds/resources. Overcoming these barriers,

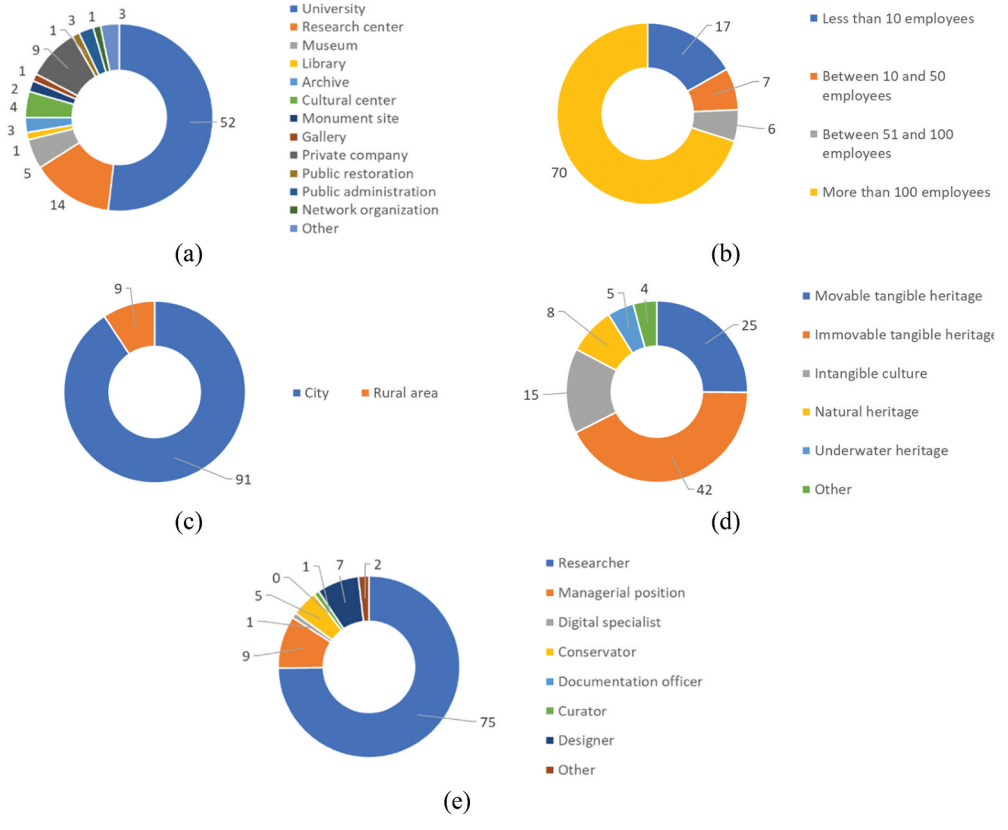

Figure 14. Demographic questions: (a) In which type of cultural heritage institution do you work? (b) How big is it? (c) Where is it located? (d) What type of cultural heritage do you work with? And (e) Which of the following options better defines your position in the field of cultural heritage?

as perceived by respondents, will require fostering skills in data analytics, creative problem solving, physically and psychologically safe work environments, as well as intercultural, inter-disciplinary, and inclusive mindset skills (see Figure 13).

To contextualise these findings, the demographic parameters (i.e. type of cultural heritage institution they work for, size of the institution, location, type of cultural heritage they work with, their position in the field of cultural heritage) of survey respondents provide valuable insights (see Figure 14). Most respondents are employed by universities, research centres, or private companies, 52 %, 14 %, and 9 %, respectively. Nearly all respondents work in urban areas (91 %), primarily within large institutions (70 % of them have more than 100 employees) and focus predominantly on immovable tangible heritage (42 %), whereas 25 % also work with movable tangible heritage and 15 % work with intangible culture. Most respondents work at a researcher position (75 %), followed by 9 % working at managerial positions, and 7 % performing the role of designers. This suggests that Industry 5.0 innovations in cultural heritage are largely research-driven, with most respondents working in universities and research centres, focusing on immovable tangible heritage in large, urban-based institutions. While there is significant interest in exploring advanced technologies for heritage conservation, the dominance of researcher

roles (75%) over managerial (9%) and designer positions (7%) indicates that these innovations are still primarily in the exploratory phase, with limited practical implementation in day-to-day operations. This points to a need for better collaboration between researchers, managers, and designers to fully integrate Industry 5.0 into heritage practices.

To strengthen the linkage between policy on Industry 5.0 and emerging practices in built cultural heritage conservation, this study suggests a clearer alignment of policy initiatives with conservation practitioners' needs and challenges. Industry 5.0, as envisioned by the EU, emphasises sustainability, resilience, and human-centrism, principles highly relevant to heritage conservation, but currently underrepresented in practice due to gaps in training, resource allocation, and awareness. Bridging this gap will require targeted policy measures that incentivise skill development, support access to enabling technologies, and foster interdisciplinary collaboration among conservation professionals. By aligning EU policy goals more closely with sector-specific needs, particularly through funding for pilot projects and the development of specialised training programmes, policymakers can facilitate a more seamless and impactful integration of Industry 5.0 principles into conservation practices.

Limitations

While respondents had the flexibility to complete the survey on different electronic devices (i.e. laptop, tablet, smartphone), the specific device used by each respondent was not recorded. This could be consider a limitation of this work, as completing questionnaires on smaller screens, such as smartphones, can extend completion time by 15 % to 40 %[45]. This factor was not considered when removing extreme outliers from the data. Moreover, the response rate may have been impacted, as studies indicate that respondents using tablets or smartphones have up to a 20 % lower questionnaire completion rate [46].

Another limitation of this study is the low adjusted response rate, which can be partly to the online survey format and the absence of incentives to encourage participants engagement, as completion was entirely voluntary. Due to time and budget constraints, a non-respondent analysis was not conducted. Nevertheless, the comparison between early and late respondents, which did not result in any significant differences between the responses of both groups, allows us to consider the results of this survey as valid and useful. Finally, it is essential to recognise that the survey has captured the perceptions of participants at the time they completed the questionnaire. Future longitudinal studies could provide a comparative picture with regards to the adoption of Industry 5.0 principles and enabling technologies among the different AECMO&C industry stakeholders.

Conclusions

This study examined the current practices and potential for adopting Industry 5.0 principles and enabling technologies in built cultural heritage conservation, focusing on perceived barriers and the skills needed to address them. Key insights were gathered through a four-parts online and fully anonymised survey targeting conservation professionals.

The findings highlight that sustainability is the most familiar and integrated of the Industry 5.0 principles among respondents, while resilience and human-centrism remain less known and adopted. This trend suggests a need for greater emphasis on these latter principles to promote a more balanced and comprehensive adoption of Industry 5.0 in heritage conservation. Additionally, the data indicate a general unfamiliarity with Industry 5.0's enabling technologies. Nevertheless, respondents recognised potential benefits, including cost reductions through enhanced resource efficiency and adaptability through training on evolving skills, reflecting a positive outlook for future integration of this transformative vision.

Regarding barriers to Industry 5.0 adoption, the most significant challenges identified were the lack of knowledge, inadequate training, and resource constraints (lack of time and funds). This is not a surprising finding, as those are some of the barriers shared by new technologies and working philosophies implementations in other fields as well. Addressing these barriers will require a multi-faceted approach that includes improved training programmes, increased funding, and fostering a collaborative mindset among professionals. Respondents noted that successful adoption of Industry 5.0 principles and enabling technologies could lead to a more accurate and detailed documentation of the built cultural heritage environment, as well as improvements in preservation and conservation practices.

In conclusion, while the importance of Industry 5.0 principles and enabling technologies is well recognised, their integration into built cultural heritage conservation remains limited. Future efforts should aim to bridge knowledge gaps, enhance training, and secure resources to overcome current barriers. By doing so, the architecture, engineering, construction, management, operation, and conservation industry can advance towards a more sustainable, resilient, and human-centric approach in heritage conservation practices. This study aims to provide a foundational understanding of the current state and future potential for Industry 5.0 adoption in heritage conservation, offering guidance to policymakers, educators, and practitioners seeking to drive innovation in this field of paramount importance for society.

Notes

1. Lasi, "Industry 4.0," 239–42.
2. Lu, "Industry 4.0: A Survey," 1–10.
3. European Commission, "Industry 5.0: Towards a Sustainable Industry."
4. European Commission, "Industry 5.0: Human-Centric, Sustainable."
5. European Commission, "Enabling Technologies for Industry 5.0."
6. Alviz-Meza et al., "Bibliometric Analysis," 189.
7. Murphy, Carew, and Stapleton, "A Human-Centred Systems Manifesto."
8. Illsley, "Digital Surrogacy," 216–34.
9. Martinelli et al., "Open HBIM-IoT Monitoring Platform," 1–18.
10. Luther et al., "Digital Twins in Museums."
11. Jiménez Rios, "Plevris, and Nogal, Bridge Management through Digital Twin."
12. Jiménez Rios, "Plevris, and Nogal, Uncertainties in Synthetic Data Generation."
13. Jiménez Rios, "Plevris, and Nogal, Synthetic Data Generation for What-if Scenarios."
14. Forster et al., "Digital Toolkit for Masonry Construction," 725–39.
15. Galassi et al., "Digital Survey on the Triumphal Arch," 940–55.
16. Masciotta et al., "Integration of Laser Scanning," 56–75.
17. European Commission, "Industry 5.0: A Transformative Vision."

18. Mourtzis, Angelopoulos, and Panopoulos, "Operator 5.0," 43–69.
19. Taj and Jhanjhi, "Towards Industrial Revolution 5.0," 285–310.
20. Asad et al., "Human-Centric Digital Twins."
21. Yang et al., "Extended Reality for Smart Crane."
22. Fraga-Lamas et al., "Mist and Edge Computing Systems."
23. Lehmann et al., "The Anatomy of the Internet of Digital Twins."
24. Li et al., "AR-assisted Safe Human-Robot Interaction."
25. Eriksson et al., "Applying Digital Twin Technology."
26. Sasikumar et al., "Blockchain-based Trust Mechanism," 16–27.
27. Chen et al., "Human-Cyber-Physical System for Wind Turbines," 1–10.
28. United Nations, "Transforming Our World: The 2030 Agenda."
29. European Commission, "Strengthening Cultural Heritage Resilience."
30. Arundel, "How to Design, Implement, and Analyse a Survey."
31. Norman, "Likert Scales and Statistics," 625–32.
32. Tehseen, Ramayah, and Sajilan, "Testing for Common Method Variance," 142–68.
33. European Parliament and Council, General Data Protection Regulation.
34. Montgomery and Runger, Applied Statistics and Probability.
35. Hendra and Hill, "Rethinking Response Rates," 307–30.
36. Jiménez Rios et al., "Survey on Industry 5.0 Concepts Dataset."
37. Sullivan and Artino, "Analyzing Likert-Type Data."
38. World Manufacturing Forum, "The 2019 Report on Skills."
39. European Commission, Survey on Collaborative Cloud for Cultural Heritage.
40. Jiménez Rios et al., "Industry 5.0 for Built Heritage Conservation."
41. ICOMOS, "Venice Charter."
42. ICOMOS, "Athens Charter."
43. van de Graaf and Hoppe, "Beleid en Politiek."
44. Jiménez Rios, Plevris, and Nogal, "Human Role in Bridge Digital Twins."
45. Toninelli and Revilla, "Mobile Device Screen Size in Surveys," 349–73.
46. Brosnan, Grün, and Dolnicar, "Web Surveys: PC, Phone, or Tablet?" 35–55.

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Data Availability Statement

The datasets generated for this study can be found in the Zenodo repository.

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Appendix A

In this appendix the questionnaire sent to the respondents is presented. As the survey was conducted online, questions were grouped and presented in separate pages. To advance through the survey, respondents needed to answer all presented questions in each page and then click a "Next" button. Each question was accompanied with an instruction, shown here within parenthesis. Demographic questions were adopted from the Stakeholders' Survey on a European Collaborative Cloud for Cultural Heritage.

Page 1: Introduction and context

Industry 4.0 has led to digitization and an increase in industrial activity. However, it has recently been recognized as inadequate for achieving European goals by 2030. As a result, a new paradigm, Industry 5.0, has emerged in response to the unexpected negative outcomes generated by its predecessor. Industry 5.0 is primarily based on three foundational

principles:

- Human-centrism
- Resilience
- Sustainability

The technologies recognized as enablers of this transformative vision are:

- Human-centric solutions and human-machine-interaction
- Bio-inspired technologies and small materials
- Real time-based digital twins and simulation
- Cyber safe data transmission, storage, and analysis
- Artificial intelligence
- Energy efficiency and trustworthy autonomy

The main goal of this survey is to explore how the architecture, engineering, construction, management, operation, and conservation (AECMO&C) industry can adapt and be better prepared to embrace novel Industry 5.0 principles and enabling technologies, ultimately resulting in enhanced built cultural heritage conservation practices.

Thank you for agreeing to participate in this important survey. To begin, please click on "Next page"

Page 2: Current practices

1.- How familiar are you with the Industry 5.0 principles? (Select your degree of familiarity with each one of the Industry 5.0 principles)

	Not at all familiar	Slightly familiar	Moderately familiar	Very familiar	Extremely familiar
Human-centrism					
Resilience					
Sustainability					

2.- To what extent are the Industry 5.0 principles currently incorporated into your work? (Select to what extent is each of the Industry 5.0 principles implemented in your work)

	Not at all	To a small extent	To a moderate extent	To a large extent	To a very large extent
Human-centrism					
Resilience					
Sustainability					

3.- How familiar are you with the enabling technologies? (Select your degree of familiarity with each one of the Industry 5.0 enabling technologies)

	Not at all familiar	Slightly familiar	Moderately familiar	Very familiar	Extremely familiar
Human-centric solutions and human-machine-interaction					
Bio-inspired technologies and small materials					
Real time based digital twins and simulation					
Cyber safe data transmission, storage, and analysis					
Artificial intelligence					
Energy efficiency and trustworthy autonomy					

4.- To what extent are these enabling technologies currently incorporated into your work? (Select to what extent is each of the Industry 5.0 enabling technologies is implemented in your work)

	Not at all	To a small extent	To a moderate extent	To a large extent	To a very large extent
Human-centric solutions and human-machine-interaction					
Bio-inspired technologies and small materials					
Real time based digital twins and simulation					
Cyber safe data transmission, storage, and analysis					
Artificial intelligence					
Energy efficiency and trustworthy autonomy					

5.- How strongly do you agree/disagree with the following sentence: "Industry 5.0 will … (Select your degree of agreement/disagreement to each one of the statements presented)

	Strongly disagree	Disagree	Neither agree nor disagree (neutral)	Agree	Strongly agree
. . . reduce cost due to resource efficiency.					
. . . empower workers by allowing them to remain in control.					
. . . create a competitive industry by attracting the best talent.					
. . . enhance adaptation by providing training for evolving skills.					
. . . give a competitive edge in new markets.					
. . . improve safety and well-being.					

Page 3: Future practices and opportunities

6.- How do you think the AECMO&C industry can better prepare to embrace Industry 5.0 principles and enabling technologies? (Select as many options as you consider relevant)

- Improved education and training.
- Greater investment in research and development.
- Better awareness and understanding of the principles.
- Greater investment in technology and infrastructure.
- More government regulations and policies.
- Adoption of standards and best practices for using these technologies.
- Other (please specify).
  - 6.1 how else do you think the AECMO&C industry can better prepare to embrace Industry 5.0 principles and enabling technologies? (text answer)

7.- What potential impacts do you foresee these changes would have on the conservation of built cultural heritage? (Select as many options as you consider relevant)

- Better preservation and protection of cultural heritage.
- Greater efficiency in conservation efforts.
- More accurate and detailed documentation of cultural heritage.
- Increased public awareness and appreciation of cultural heritage.
- Early adoption and non-tested applications resulting on inappropriate interventions.
- Negligible impact in this field.
- Other (please specify).
  - 7.1 What other potential impacts do you foresee these changes would have on the conservation of built cultural heritage? (text answer)

Page 4: Barriers

8.- What do you perceive as the main barriers to the adoption of Industry 5.0 principles and enabling technologies in your work? (Please provide your answer as a list of perceived barriers. Separate each barrier description by a semicolon ";". Your answer is limited to 1000 characters).

9.- How can these barriers be overcome? (Rank the following concepts, which correspond to the top ten skills for the future as identified at the World Manufacturing Forum, based on how helpful you think they could be to overcome the barriers you perceive, being 5 as very helpful and 0 as not helpful at all)

- Digital literacy.
- AI and data analytics.
- Creative problem solving.
- Entrepreneurial mindset.
- Physically and psychologically safe work environments.
- Inter-cultural, inter-disciplinary, and inclusive mindset.
- Privacy and data mindfulness.
- Multitasking.
- Communication skills.
- Open-mindedness towards constant change

Page 5: Demographics

10.- In which type of cultural heritage institution do you work? (Select as many options as relevant)

- University
- Research Centre
- Museum
- Library
- Archive
- Cultural Centre
- Monument Site
- Gallery
- Private Company Active in the Cultural and Creative Industries
- Public Restoration and Conservation Enterprise
- Public Administration
- Network Organization
- Other

11.- How big is it? (Select one option only)

- Less than 10 Employees
- Between 10 and 50 Employees
- Between 51 and 100 Employees
- More than 100 Employees

12.- Where is it located? (Select one option only)

- City
- Rural area

13.- What type of cultural heritage do you work with? (Select as many options as relevant)

- Movable tangible heritage (books, documents, movable artworks, machines, clothing, etc.)
- Immovable tangible heritage (buildings, monuments, etc.)
- Intangible culture (folklore, traditions, language, knowledge, etc.)
- Natural heritage

- Underwater heritage
- Other

14.- Which of the following positions define yours better in the field of cultural heritage? (Select one option only)

- Researcher
- Managerial Position (Programme/Project Manager)
- Digital Specialist
- Conservator
- Documentation Officer
- Curator
- Other