



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

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Abstract

Despite being adopted only recently, Industry 5.0 has already attracted significant attention from researchers in various fields. However, the Architecture, Engineering, Construction, Management, Operation, and Conservation (AECMO&C) industry, particularly in the context of built cultural heritage conservation, has been left behind. Thus, the aim of this work is to better understand the perceptions of conservation professionals regarding the adoption of Industry 5.0 principles and enabling technologies, the perceived barriers and needed skills to overcome them. A survey questionnaire has been designed, tested, and implemented. After analysing and discussing the information collected, it has been concluded that while there is a clear recognition of the importance of Industry 5.0 principles and enabling technologies, their adoption in built cultural heritage conservation remains limited. Future efforts should focus on bridging knowledge gaps, enhancing training, and securing resources to overcome existing barriers.

Keywords

Industry 5.0, Human-Centrism, Resilience, Sustainability, Built Cultural Heritage Environment, Conservation.

1. Introduction

Cultural heritage conservation practice has benefited from some of the technological progress developed during Industry 4.0 in recent years [1]. Some applications include the enhanced experience of visitors at cultural places through extended reality [2], advances in the understanding of cities cultural heritage using virtual reality models [3], the use of digital twins to improve the conservation of museum collections [4] and to optimize historical bridges management and operations [5-7]. Although Industry 4.0 developments have driven a growth in productivity and the digitalization of many industrial activities, this has also resulted in significant drawbacks, such as a negative impact in the environment and a negative perception towards the potential risk that an automatized industry might pose to the human workforce component. Thus, Industry 4.0 has been deemed inadequate to achieve sustainability goals and to provide a satisfactory framework to face the threats risen by socio-economic inequalities and climate change [8].

Therefore, a novel transformative vision, as described by the European Union, has emerged. This new paradigm has been labelled “Industry 5.0” and it is presented not as a replacement of Industry 4.0, but as a revised and enhanced version [9]. Industry 5.0 has been developed around three core principles aiming at incorporating the concepts of sustainability, resilience, and human-centrism. Moreover, the operationalization of such principles has been deemed feasible through the implementation of a series of technologies that would enable to obtain benefits such as reduced costs, empowered workers, attract best talent, adapted training for evolving skills, competitive edge in new markets, and overall improved safety and well-being conditions [10]. Individualized human-machine-interaction, bio-inspired technologies and smart materials, digital twins and simulation, data transmission, storage, and analysis technologies, artificial intelligence, and energy efficiency and trustworthy autonomy are the recognized enabling technologies of Industry 5.0 [11]. Despite being a relatively recent development, Industry 5.0 has already attracted significant attention from researchers. Its fundamental concepts and technologies have been explored [12-14], innovative implementation frameworks have been suggested [15-17], and applications in fields such as manufacturing [18], education [19], data privacy [20], and wind energy infrastructure [21] have been conducted. However, the Architecture, Engineering, Construction, Management,

Operation, and Conservation (AECMO&C) industry, particularly in the context of built cultural heritage conservation, has been left behind and proactive efforts are needed if a successful adoption of Industry 5.0 principles and enabling technologies is to be achieved.

In this work, built cultural heritage refers to man-made structures, buildings, landmarks, and spaces with historical, architectural, artistic, cultural, or social significance. The United Nations (UN) have recognized in its Sustainability Development Goals (SDG) that safeguarding cultural heritage contributes to making cities and human settlements inclusive, safe, resilient, and sustainable [22], and it is now well understood that efforts to preserve the built cultural heritage environment are both required and desired [23]. Thus, the aim of this work is to better understand what the perceptions of conservation professionals are regarding the adoption of Industry 5.0 principles and enabling technologies. We seek to shed light into the current practices, future potential benefits, identify barriers and the required skills needed to overcome them, so that ultimately, a successful adoption can be carried out and the benefits offered by this transformative vision can be exploited to the maximum.

2. Materials and methods

Within this section we present the details regarding the survey questionnaire design, testing, and implementation, as well as the analyses conducted on the collected data. The overall methodology is presented in Figure 1 and a full version of the implemented questionnaire is provided in Appendix A.

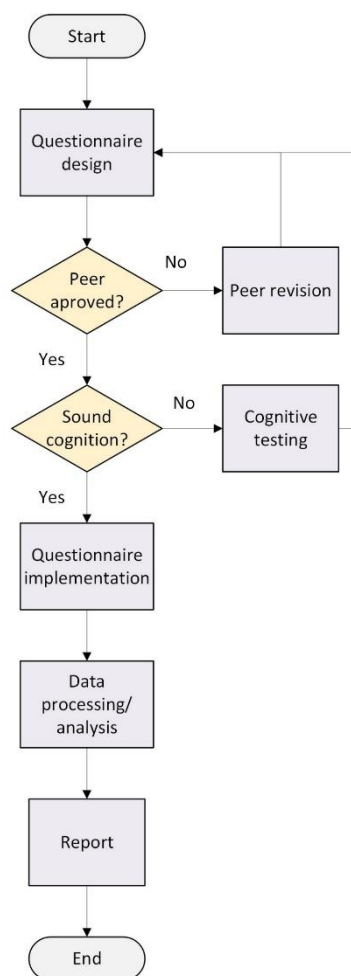


Figure 1. Overall methodology followed to conduct the survey.

2.1. Questionnaire design

The survey conducted was an exploratory cross-sectional study, which allows to look for plausible causal relationships between variables [24]. Its aim was to better understand the perception of different stakeholders in the field of built cultural heritage environment conservation regarding Industry 5.0 principles and enabling technologies. Thus, respondents were consulted only once and were asked about their personal experiences with this transformative vision fostered by the European Union.

A structured questionnaire was designed. A mix of single choice (Likert scale [25]), multiple choice, and open question types were used as different types of questions are more suitable than others to obtain meaningful information in different topics. This variety of question types was also used with the purpose of avoiding monotony and boredom in the respondents. More importantly, the selected mix of question types has been implemented to avoid common method bias [26] and satisficing behaviour from respondents.

As this survey was conducted online and self-administered, it was decided to place the most interesting questions at the beginning of the questionnaire to catch the respondent's attention, while demographic questions were left near the end. Replying to all questions was mandatory to successfully complete the questionnaire. This was done with the aim of reducing missing data and incomplete submissions.

The questionnaire form was created in Nettskjema (<https://nettskjema.no/>), which is a web-based survey tool developed by the University of Oslo, Norway, that allows creation, storage, and management of surveys. This software automatically performs data collection and provides a summary report after the survey is closed. Moreover, a data coding was conducted with the aim of facilitating the collected data analysis.

2.2. Questionnaire testing

The first version of the questionnaire was developed by the first author of this article. On a first questionnaire testing step, two co-authors of the manuscript revised it and provided their feedback to the first author, who implemented some minor changes to improve the quality and clarity of the questionnaire. During this first testing step, skip routines were tested and validated. Minor language errors were fixed as well.

At a second questionnaire testing step, a cognitive testing was conducted. The main objective was to determine if specific questions will obtain accurate, meaningful, and comparable data from potential respondents, as well as to test questionnaire structure, completion time, language, among other minor aspects. It consisted of a single phase of testing and involved the remaining two co-authors of this work as well as other experts in the field of built cultural heritage conservation, for a total of seven interviewees.

The cognitive testing was conducted in conditions mirroring those in which final respondents would engage with the survey, i.e., the interviewees received the invitation email, they were asked to either click on the access link or access the survey via the QR code. They were let alone to progress through the completion of the survey (self-administered). After that, they were asked to provide feedback in the different stages of the survey completion (invitation email, questionnaire design, graphical user interface, language used, etc.) and their feedback was collected and analysed. Based on the feedback received from these group of respondents, the questionnaire was further improved with minor revisions of the questions before it was finally distributed among the final respondents.

Although desirable, but not necessarily compulsory [24], the pilot survey testing step has been skipped. This was due to time and budgetary constraints, as well as to the difficulty of obtaining high response rates through the online implementation only.

2.3. Questionnaire implementation

The survey was conducted online. This online method was selected due to its low cost, fast delivery, and automated collection of data through the Nettskjema tool. Furthermore, the online application of the survey also presents advantages in terms of improved data quality, as it can automatically detect unanswered questions, and uses automated filter instructions, which reduced the burden of respondents. Nevertheless, the advantages of this method are also accompanied by an expected low response rate. It was expected to obtain 11 to 12 percentage points lower response rates, as it has been observed in comparison to other survey methodologies such as telephone interviews, face-to-face interviews, and postal survey [24].

Respondents accessed the form either by clicking on a link or by scanning a QR code and were allowed to reply to the questionnaire using either a desktop, tablet, or mobile phone. Every respondent was allowed to answer the survey only once. An invitation email containing key information about the survey as well as the access link and QR code was sent on 4 March 2024 (Monday). The survey remained opened for four weeks, and a reminder email was sent on 25 March 2024 (Monday), one week before the survey was closed. Finally, on 31 March 2024 (Sunday) the survey was closed, and the collection of the survey data was completed.

The data entry was automatically done by the software and stored into a data file in .csv format. Unfortunately, no data about the device (i.e., laptop, mobile, tablet) used to complete the software was captured, either explicitly through a question part of the survey, nor through automatic software device recognition feature. By making all questions compulsory, we ensured that all submitted questionnaires were fully responded, although this may have hindered the response rate, and half attempts have not been recorded.

The population of interest were experts and stakeholders on the conservation of the built cultural heritage environment. Although it is not possible to accurately determine the population size, it was intended to invite as many respondents as possible to participate in the survey. Thus, a search of corresponding authors in journals related to the field of cultural heritage was conducted on 09/02/2024. Scopus was selected as the online database to search for the bibliographic data of all records published in a selection of 25 journals, obtaining a total of 18,478 entries (see Table 1). After cleaning the information pertaining to the corresponding authors of the records (deduplication, removal of missing data, etc.), we ended up with a sample frame of 8,311 subjects. Due to an expected low response rate (i.e., online survey, voluntary), a census method was adopted, meaning that the sample fraction size was equal to the sample frame.

The survey was only conducted in English, regardless of the variety of nationalities and languages among the respondents, as it was expected that they all had a good level of English, as they had successfully published research in international journals. The answer time of every respondent was recorded (paradata) and used to identify satisficing behaviour and remove speeders. As the survey was fully anonymized, the breach of any ethical issues related to personal data was avoided in compliance with General Data Protection Regulations (GDPR) [27]. Furthermore, attention was paid to avoid harming any of the respondents, protect their confidentiality and privacy, and by being a voluntary survey, the consent of those who participated was implicitly obtained.

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

2.4. Data processing

Both crude and adjusted response rates were computed using the number of responses received. The first rate was based on the number of invitation emails sent, whereas the second one was based on the number of delivered invitation emails. As the survey was fully anonymised, no individual tracking data was stored. On the other hand, the date in which every response was received was collected to monitor the response behaviour. This information may be important as sometimes different behaviours could have been observed between early and late respondents.

The first stage of the data processing consisted in the removal of extreme outliers and speeders. For that purpose, the paradata collected on the time of survey completion was exploited. Outliers were identified using a box plot and extreme outliers, i.e., points more than three times the interquartile range from the box edge [28] were removed. Then, the mean time of reply was computed, and those responses completed in less than one third the average completion time were labelled as speeders and were excluded, as well.

The questionnaire was manually coded before it was distributed. This was done inside the Nettskjema tool, and the coding adopted was also useful to export the collected data, which was later analysed using statistical software (SPSS and Excel were the tools used in this case). Likert items were analysed by computing their mode, median, and by visualizing the data on

bar chart plots. The open question (question 8) was analysed and interpreted through a words map. Finally, the demographics data was studied after plotting it as pie charts.

3. Results

Bibliographic data from 18,478 records was found in Scopus on 09/02/2024 (see Table 1). After cleaning and deduplication, 8,311 records remained, including 12 unrecognizable emails. Thus, 8,299 invitation emails were sent, out of which 6,577 were successfully delivered. By the time the survey was closed, 115 replies had been received. Therefore, the crude response rate is 1.4% and the adjusted response rate is 1.7%. The main reasons for receiving such a small response rate are linked to the modality of the survey (online) and to its full voluntary participation. Although this adjusted response rate was relatively low, limitations in both budget and time, prevented us from conducting a non-respondent analysis.

As this was a fully anonymised survey, no personal data was collected, processed, nor stored, and no ethical issues were breached. This also removed the need for anonymizing the responses received. On the other hand, this work has been funded by the European Union and the raw data collected from the respondents has been made publicly available, see [29], in compliance with open science policies.

The submission frequency of the survey is presented in Figure 2. From this figure it can be observed that most responses (56) were collected in the first day of the survey. Few other responses followed during the rest of the first week of the survey (32 between March 5 and 10). Very few responses were collected between the second and third weeks of the survey (8). There was a slight increase in submissions during the first two days of the final week, coinciding with the reminder email. No further responses were received in the last two days of the survey.

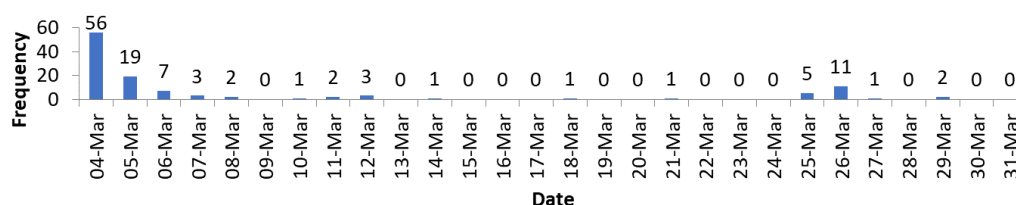


Figure 2. Response frequency. Survey started on 04/03/2024 and was closed on 31/03/2024.

By first converting the survey completion time to minutes, and then analysing this data, the interquartile (IQ) values obtained were: $IQ1=5.43$, $IQ2=8.03$, $IQ3=11.31$, which gives an interquartile range (IQR) of 5.88 (see Figure 3). This results in a threshold value of 28.95 min to identify extreme outliers, which resulted in the exclusion of five responses from the following data analysis. The mean survey response time of the remaining 110 responses collected was 9 min. It was decided to label those responses completed in less than a third of this time as speeders, which is a clear sign of satisficing behaviour. Thus, three responses were identified and consequently removed, which ultimately resulted in 107 responses considered as valid.

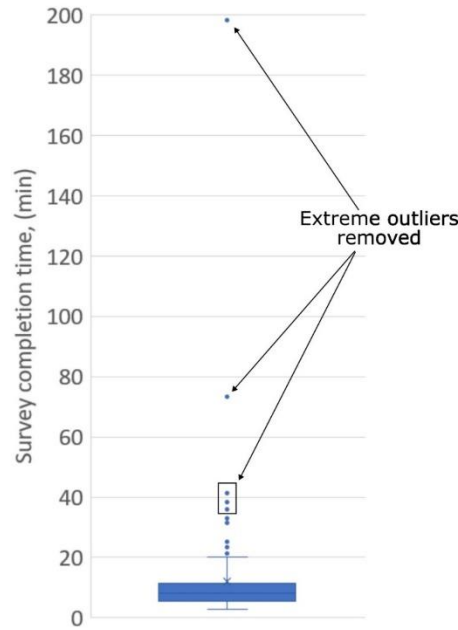


Figure 3. Detection and removal of extreme outliers based on survey completion time (min).

Most of the common errors committed while respondents answer questionnaires (i.e., entering illogical or ineligible responses, submitting incomplete responses, etc.) were avoided by using an online format. Moreover, missing values were minimized by making every question compulsory for the completion of the survey. Nevertheless, some of the answers received in question 8 (see full survey on Appendix A) may be considered as missing values. For instance, “-”, “/”, “?”, “n/a”, “x”, “not sure”, “I need more information”, “I have no idea” could all be considered as missing values, as none correspond to what could be considered a barrier for the adoption of Industry 5.0. On the other hand, “none” would be considered as a valid answer for this case, which indicates that the respondent is not aware of any possible barrier. In total, 18 replies were “missing”, representing a 16.8%. As this is an open text question asking for a list of items, the valid responses collected varied significantly. Some respondents provided just one barrier, whereas others gave several ones. Due to the nature of the question and the responses obtained, it was considered unnecessary (and unfeasible) to apply any imputation method to fill up the missing values.

3.1. Current practices

Within the first part of the questionnaire, we aimed at shedding light into the current practices among the conservation professionals’ community. Table 2 presents the measurements of central tendency, that is, mode and median, appropriate for the analysis of Likert scale data [30] for all questions on this part of the questionnaire. Questions 1 and 2 were related to the core principles of Industry 5.0, whereas questions 3 and 4 dealt with its enabling technologies. Moreover, question 5 allowed showing the degree of agreement of the respondents with what has been highlighted as the benefits of Industry 5.0 adoption by the European Union [10].

Figure 4 (a), (b), and (c) show the respondents perception with regard to the degree of familiarity with the principles of human-centrism, resilience, and sustainability, respectively. On the other hand, Figure 5 presents the extend of adoption of such principles within the current work practice of the respondents. Similarly, Figure 6 and Figure 7 present the familiarity perception and degree of implementation of the identified enabling technologies of Industry 5.0. Finally, Figure 8 presents the respondents agreement with regards to the intended benefits of a successful adoption of Industry 5.0. Figure 8 (a) is related to costs reduction due to

resources efficiency, (b) to the empowerment of workers by allowing them to remain in control, (c) to an enhance industry competitiveness thanks to the attraction of best talent, (d) to the adaptation of training programs on evolving skills, (e) to the competitive edge given in new markets, and finally (f) to the generalized improvement on safety and well-being.

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

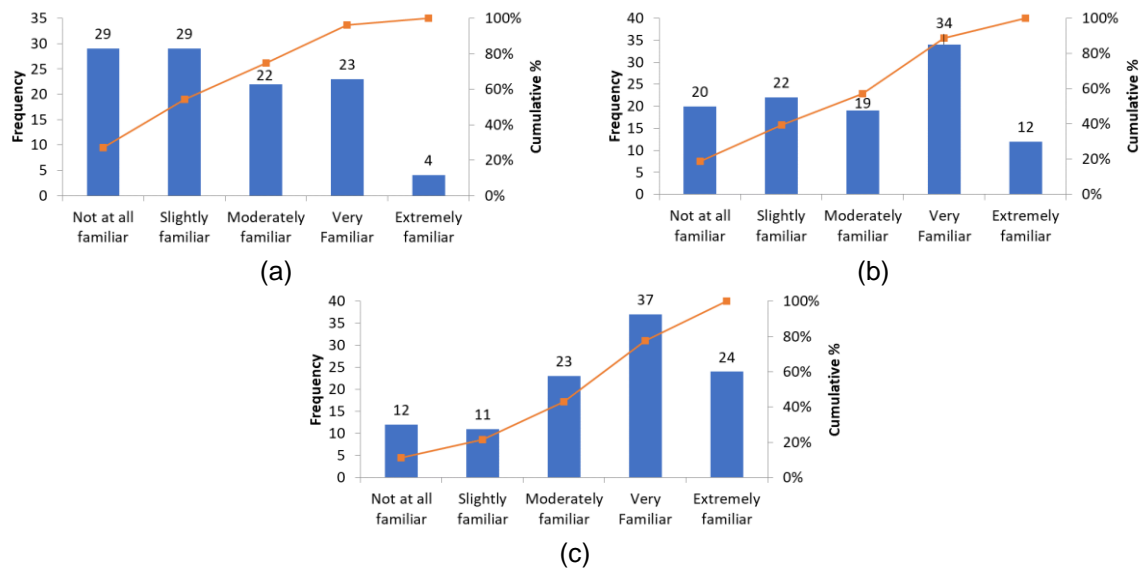


Figure 4. Question 1: How familiar are you with the Industry 5.0 principles? (a) human-centrism, (b) resilience, and (c) sustainability.

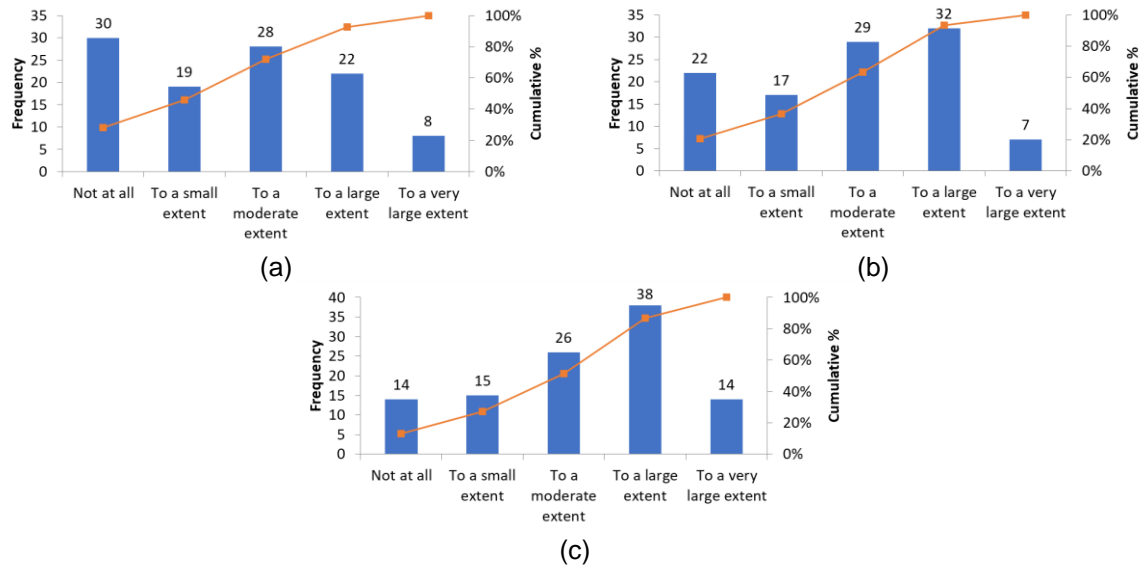


Figure 5. Question 2: To what extent are the Industry 5.0 principles currently incorporated into your work? (a) human-centrism, (b) resilience, and (c) sustainability.

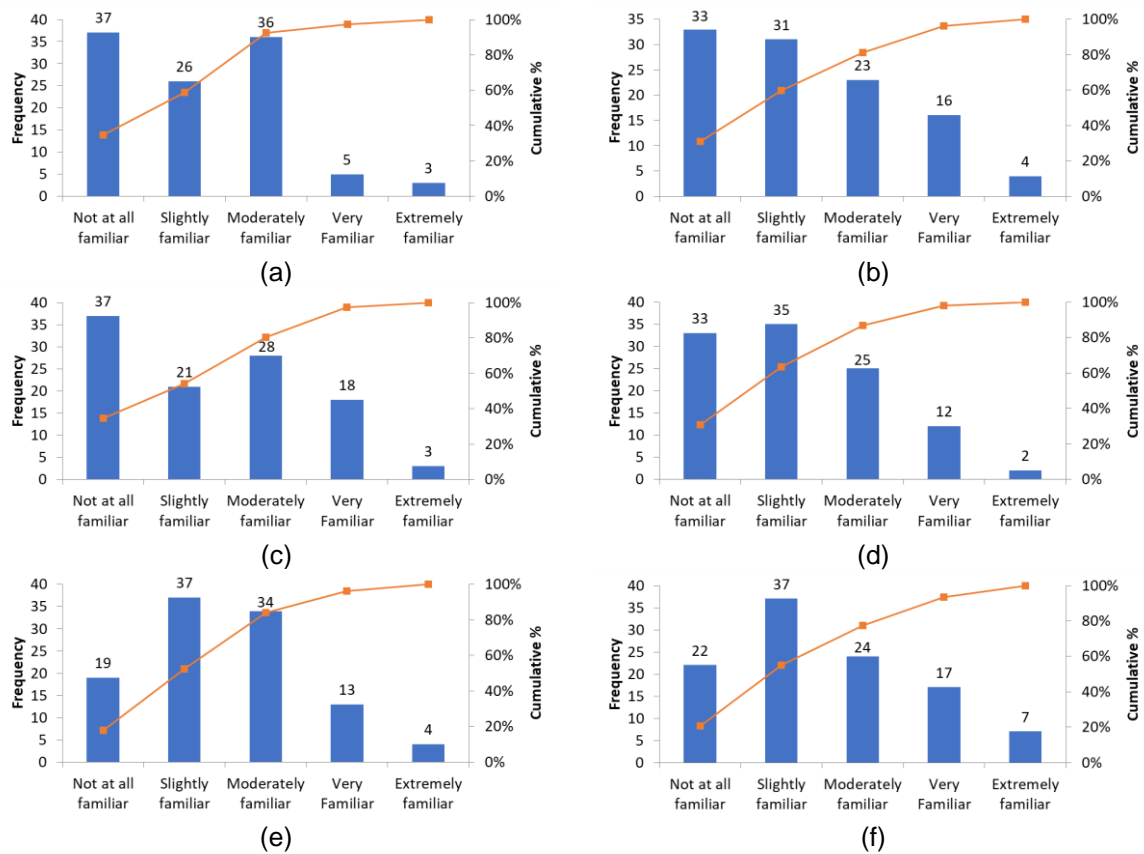


Figure 6. Question 3: How familiar are you with the enabling technologies? (a) human-centric solutions and human-machine interaction, (b) bio-inspired technologies and smart materials, (c) real time-based digital twins and simulation, (d) cyber safe data transmission, storage, and analysis, (e) artificial intelligence, and (f) energy efficiency and trustworthy autonomy.

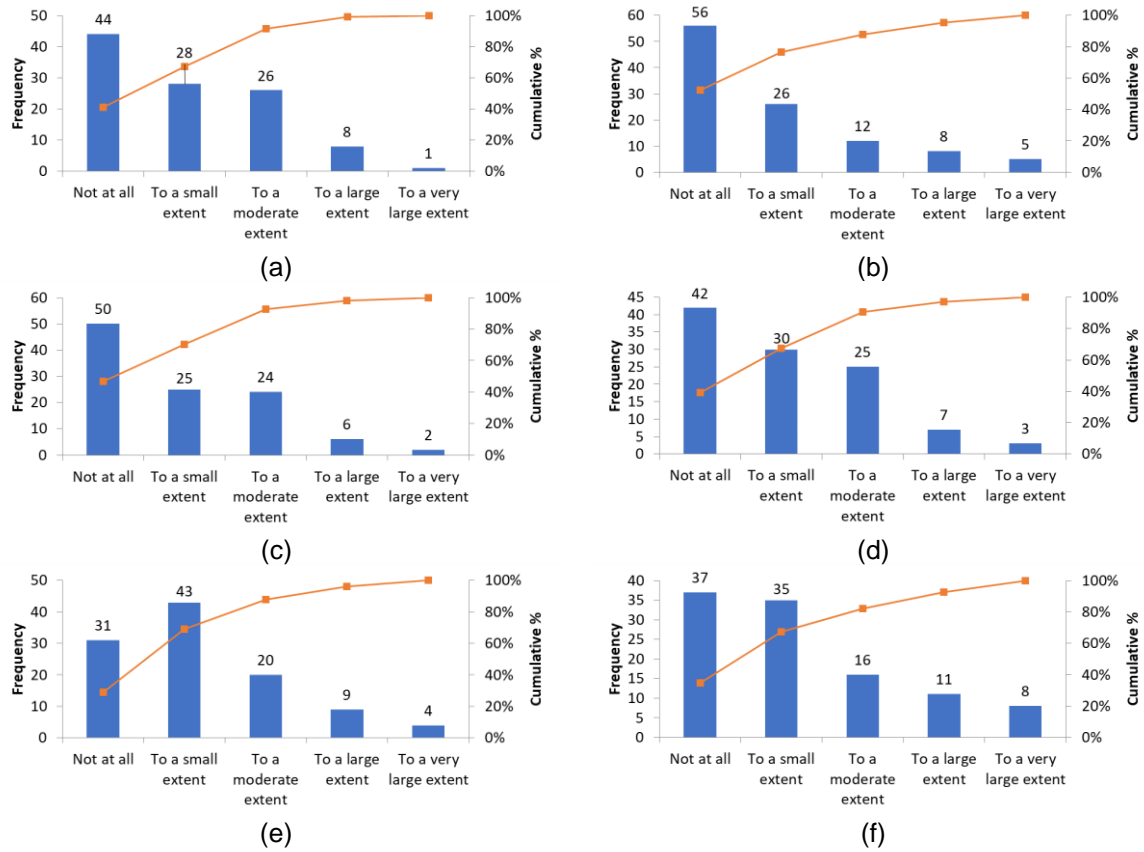


Figure 7. Question 4: To what extent are these enabling technologies currently incorporated into your work? (a) human-centric solutions and human-machine interaction, (b) bio-inspired technologies and smart materials, (c) real time-based digital twins and simulation, (d) cyber safe data transmission, storage, and analysis, (e) artificial intelligence, and (f) energy efficiency and trustworthy autonomy.

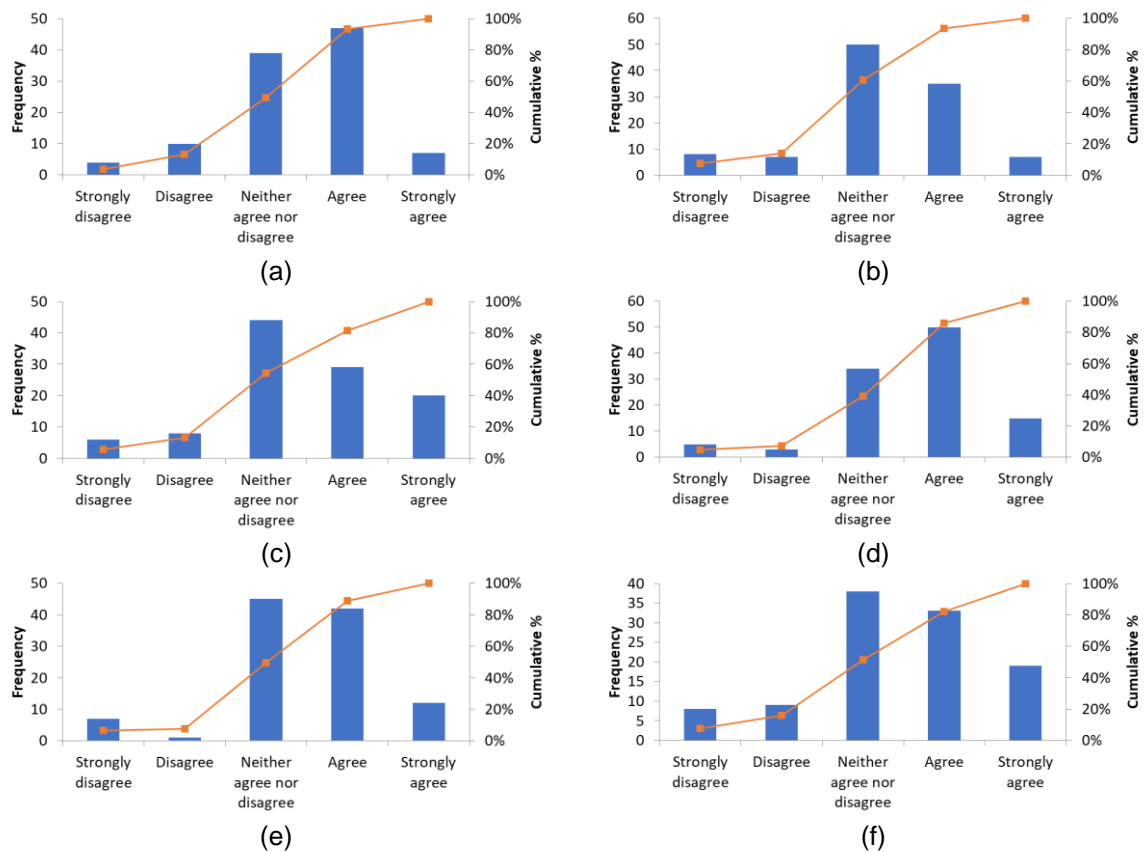


Figure 8. Question 5: How strongly do you agree/disagree with the following statements: “Industry 5.0 will... (a) reduce cost due to resource efficiency, (b) empower workers by allowing them to remain in control, (c) create a competitive industry by attracting the best talent, (d) enhance adaptation by providing training for evolving skills, (e) give a competitive edge in new markets, and (f) improve safety and wellbeing.

3.2. Future practices and opportunities

Questions 6 and 7 dealt with the future practice prospectives and the respondents’ perspectives about preparation measurements and potential impacts. Besides from a series of predefined concepts provided as answer to these multiple-choice questions, respondents were given the opportunity of selecting the “other” option and write in text their complementary ideas.

Figure 9 shows the percentage of respondents who selected the different preparation strategies proposed; multiple selection was allowed. On the other hand, Figure 10 highlights the respondents’ perceptions of the potential impacts that the adoption of this novel paradigm could have on the conservation of built cultural heritage.

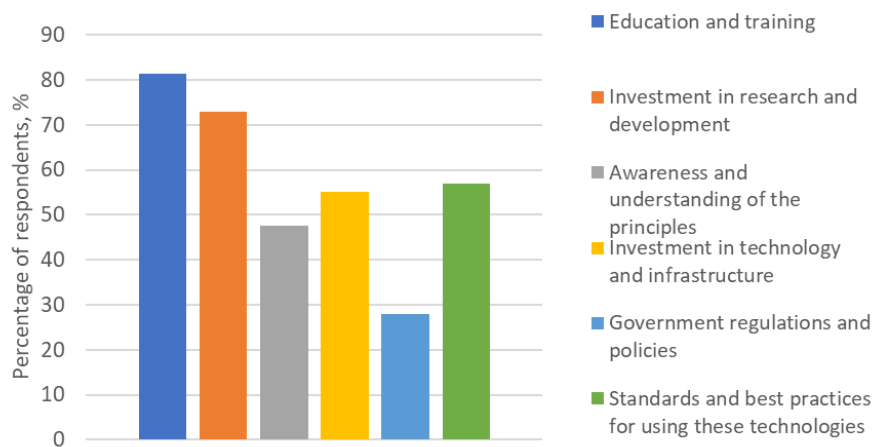


Figure 9. Question 6: How do you think the Architecture, Engineering, Construction, Management, Operation, and Conservation (AECMO&C) industry can better prepare to embrace Industry 5.0 principles and enabling technologies?

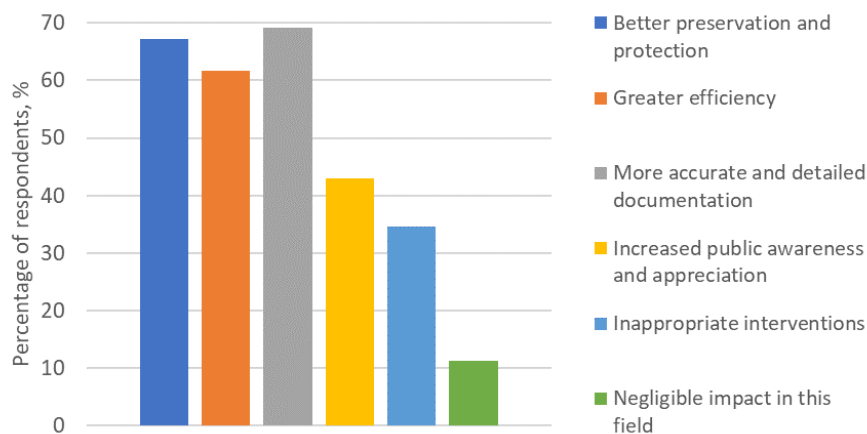


Figure 10. Question 7: What potential impacts do you foresee these changes would have on the conservation of built cultural heritage?

3.3. Barriers

The third part of the questionnaire was dedicated to the foreseen barriers perceived by the respondents for the adoption of Industry 5.0 in the field of built cultural heritage environment

conservation as well as on the possible skills needed to overcome them. Question 8 was an open-answer question type. Thus, the answers collected have been analysed qualitatively and presented in the form of a word cloud in Figure 11.



Figure 11. Question 8: What do you perceive as the main barriers to the adoption of Industry 5.0 principles and enabling technologies in your work?

On the other hand, question 9 enquired into a series of concepts identified at the World Manufacturing Forum as the top ten skills for the future [31], and the perception of the respondents on their actual degree of usefulness to overcome the barriers indicated in question 8. Figure 12 presents the stacked bar plot with the classification level assigned to each skill by the respondents of this survey, being 0 not useful at all, and 5 very useful. Both the mean and mode of the answers collected in question 9 corresponding to each of the identified skills are presented in Table 3.

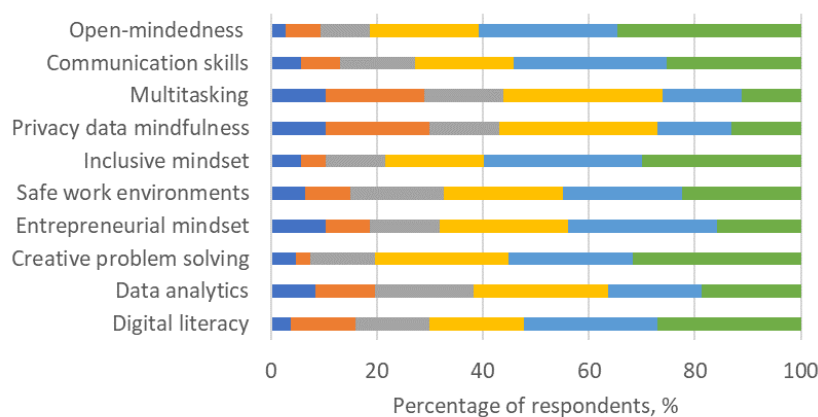


Figure 12. Answers to question 9: How can these barriers be overcome? (the indicated skills were ranked based on how helpful respondent thought they could be used to overcome the barriers they perceived, being 5 as very helpful and 0 as not helpful at all).

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

3.4. Demographics

Finally, the fourth and last part of the survey, consisted of a series of questions dealing with demographic parameters of the respondents. Similar questions used on other cultural heritage surveys [32] were used and slightly adapted to investigate the type of cultural heritage institution the respondents work in, the size of the institution, its location, the type of cultural heritage asset it focuses on, and the position of the respondents within such institution. The data collected is presented in the form of pie charts (see Figure 13).

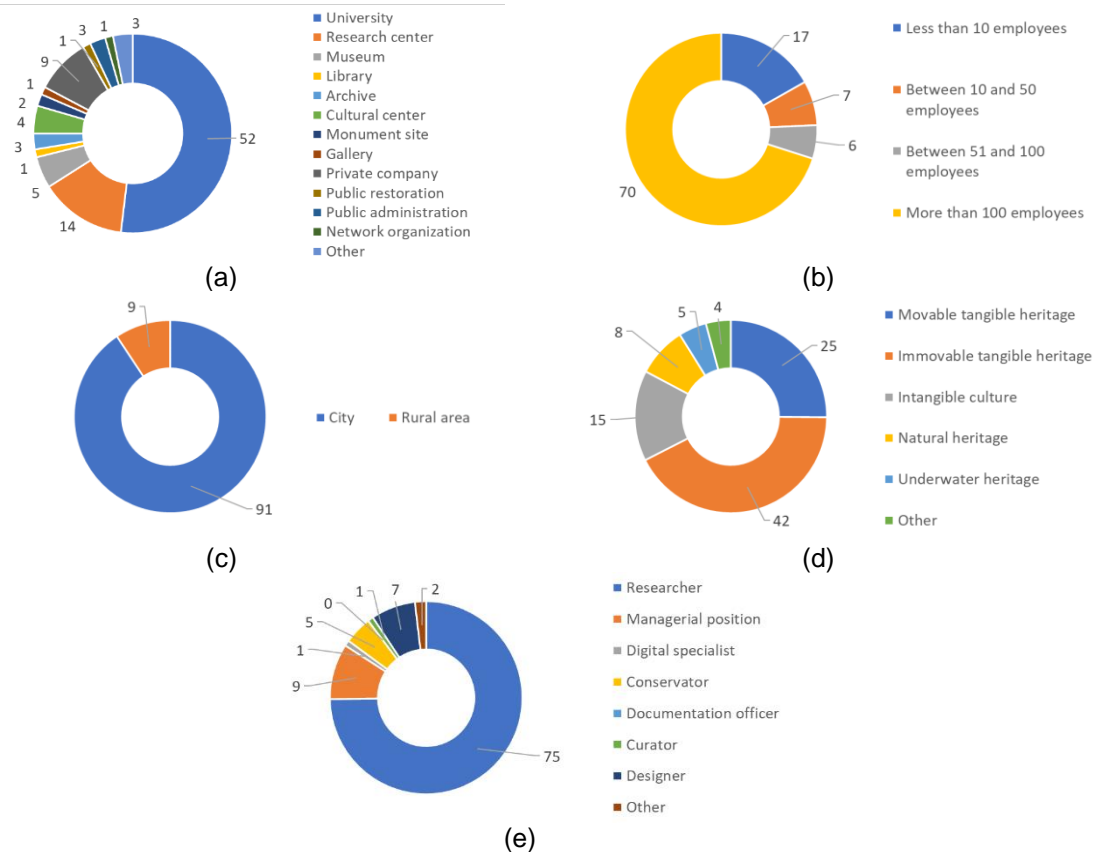


Figure 13. Demographic questions: (a) In which type of cultural heritage institution do you work? (b) How big is it? (c) Where is it located? (d) What type of cultural heritage do you work with? and (e) Which of the following options better defines your position

4. Discussion

After conducting a systematic literature review, Jiménez Rios et al. [33] noticed that among the three core principles of Industry 5.0, the research community working on the field of built cultural heritage conservation has mainly focused their efforts on the adoption of sustainability.

This observation is further confirmed by the data collected from this survey in question 1, which could be interpreted at the personal level of the respondents. While most participants are either very familiar or extremely familiar with sustainability ($Q1_SQ1_{median} = 4$), most of them are only moderately familiar with resilience ($Q1_SQ2_{median} = 3$) and the majority of respondents consider themselves either only slightly familiar or not at all familiar with human-centrism ($Q1_SQ3_{median} = 2$). On the other hand, question 2 provides a sort of institutionalised view, as respondents were asked about the degree of adoption in their works, which could be influenced by corporative policies and mindsets. In this case, all principles presented a moderate extent of incorporation ($Q2_SQ1,2,3_{median} = 3$), although the majority of respondents identified sustainability and resilience as incorporated into their work to a large extent ($Q2_SQ2,3_{mode} = 4$) and the majority of repliers mentioned that human-centrism was not at all incorporated into their work ($Q2_SQ1_{mode} = 1$).

These differences between the personal and institutional current practices are not observed when we consider the enabling technologies of Industry 5.0. From the data collected in question 3 it can be observed that most respondents are only slightly familiar with all enabling technologies ($Q3_SQ1,2,3,4,5,6_{median} = 2$). Similarly, they recognized 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 have mostly not being at all incorporated in their current conservation practices ($Q4_SQ2_{median} = 1$). This scenario sheds light into the urgent need to foster the implementation of novel technologies within the field of built cultural heritage conservation. However, this may be hindered by global inequalities and the conservative approach adopted in conservation charters [34] and the need of fully proving the suitability of novel materials on conservation applications.

In terms of the benefits that the adoption of Industry 5.0 principles and enabling technologies can bring to the field of built cultural heritage conservation (see Figure 8), the perception of the respondents can be classified either as neutral or slightly positive. Whereas most respondents think that this novel paradigm would neither empower workers, attract best talent, give a competitive edge in new markets, or improve safety and wellbeing ($Q5_SQ2,3,5,6_{mode} = 3$), the majority of the repliers agree with the idea that it may reduce costs due to an improved efficiency, and enhance adaptation by providing training for evolving skills ($Q5_SQ1,4_{mode} = 4$). This data allows us to identify the perceptions of the community and direct the necessary resources towards the adequate changes and measurements to achieve a successful adoption of this transformative vision.

In this regard, the survey has also highlighted a tentative path to follow. In question 6 respondents have identified the means for the AECMO&C industry to be better prepared and embrace Industry 5.0 principles and enabling technologies. More than 80 % of the respondents think that an improved education and relevant training, along with greater investment in research and development (73 %) would be the two most significant measurements to achieve a successful adoption of this novel paradigm. Other preparation measurements suggested by respondents include the participation of the community, the involvement of practitioners in policy development, and the raising of public awareness. Greater investment in technology and infrastructure, and the adoption of standards and best practices for using Industry 5.0 enabling technologies have also been considered as adequate for the preparation of conservation professionals by 55 % and 57 % of respondents, respectively. If adequately implemented, these changes would result in more accurate and detailed documentation of cultural heritage (69 %), better preservation and protection of cultural heritage (67 %), and greater efficiency in conservation efforts (62 %). Despite the overall atmosphere of positivism shown by most respondents, it is worth noticing that 35 % of the respondents considered that

an early adoption of these novel (and not yet fully understood) technologies may lead to cases of inappropriate interventions. Such scenarios have occurred in the past, e.g. after the adoption of the Athens Charter [35] and the encouragement of using modern techniques and materials in restoration works, which led to the inappropriate use of reinforced concrete, a novel technology during the early 20th century, and efforts should be made to avoid the repetition of these inadequate conservation practices.

The adoption of Industry 5.0 principles is an “untamed” problem, as described by van de Graaf and Hoppe [36] as it requires a large degree of social consensus and involves a high degree of technological uncertainty. Thus, this problem requires a multi-actor engagement and agreement to be solved [37]. Among the most common barriers perceived by the respondents of the survey for the adoption of Industry 5.0 (see Figure 11), the lack of knowledge about the principles, lack of adequate training to handle its enabling technologies, and the lack of funds/resources were mentioned by most respondents. Nevertheless, such barriers could be overcome if data analytics, creative problem solving, physically and psychologically safe work environments, as well as inter-cultural, inter-disciplinary, and inclusive mindset skills are fomented among the community of conservation professionals as perceived by the respondents of this survey (see Figure 12).

To better understand the context of the data collected through this survey and the background of the respondents along with their corresponding perceptions, it is worth discussing the main demographic parameters. As presented in Figure 13, most respondents work at a university, research centre, or private company, 52 %, 14 %, and 9 %, respectively. While most heritage institutions where respondents work are in an urban area (91 %), 70 % of them have more than 100 employees, whereas only 17 % of them has only less than 10 employees. Respondents work mostly with 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.

4.1. Limitations

Although respondents were able to complete the survey in different electronic devices (i.e., laptop, tablet, smartphone), the device used by every respondent was not recorded. This could be seen as a limitation of this work in the sense that due to a smaller screen size, the completion of questionnaires in smartphones may take between 15 % to 40 % longer [38]. This factor has not been considered in the deletion of extreme outliers in the data. Moreover, the response rate may have been negatively affected as well, as it has been observed that respondents using a tablet or a smartphone result in 20 % lower questionnaire completion rates [39].

Another evident limitation is the low adjusted response rate obtained, which is partially justified by the type of survey implementation (online) and the lack of incentives to motivate invited participants to complete the survey (completion was fully voluntary). Moreover, due to time and budget limitations, a non-respondent analysis was not conducted. Finally, the survey has captured the perceptions of participants in the time when they replied to the questionnaire. Future longitudinal studies may provide a comparative picture with regards to the adoption of Industry 5.0 principles and enabling technologies among the different AECMO&C industry stakeholders.

5. Conclusions

This work investigated the current and prospective practices related to the adoption of Industry 5.0 principles and enabling technologies within the context of built cultural heritage conservation, as well as the perceived barriers, and needed skills to overcome them, were investigated. Several key insights have been drawn through a four-parts online and fully anonymized survey targeting conservation professionals.

The first aspect highlighted by this research was that the sustainability principle is the most familiar and integrated Industry 5.0 principle among respondents, whereas resilience and human-centrism are less known and adopted. This trend suggests a need for greater emphasis and education on the latter two principles to ensure a holistic approach towards the adoption of Industry 5.0 in heritage conservation. The data also revealed a general unfamiliarity with enabling technologies of Industry 5.0. Despite this, respondents acknowledged the potential benefits of these technologies, including cost reductions due to enhanced resource efficiency and improved adaptability through training on evolving skills. This indicates a positive outlook on the future integration of this transformative vision.

Considering the perceived Industry 5.0 barriers, the most significant challenges identified were the lack of knowledge, insufficient training, and resource constraints (lack of time and funds). Addressing these barriers will require multi-faceted strategies, including improved training programs, increased funding, and fostering a collaborative mindset among professionals. It has been recognized by the respondents that if successfully adopted, Industry 5.0 principles and enabling technologies could mainly be reflected on a more accurate and detailed documentation of the built cultural heritage environment, along with overall enhanced preservation and conservation practices.

In conclusion, while there is a clear recognition of the importance of Industry 5.0 principles and enabling technologies, their adoption in built cultural heritage conservation remains limited. Future efforts should focus on bridging knowledge gaps, enhancing training, and securing resources to overcome existing barriers. By doing so, the architecture, engineering, construction, management, operation, and conservation industry can move towards a more sustainable, resilient, and human-centric approach on heritage conservation practices. Overall, we hope that this study provides a foundational understanding of the current state and future prospects of Industry 5.0 adoption in heritage conservation, serving as a guide for policymakers, educators, and practitioners aiming to foster innovation in this area of paramount importance.

Declaration of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be considered as a potential conflict of interest.

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Data availability statement

The datasets generated for this study can be found in the Zenodo repository [29].

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Annex 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 [32].

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

Annex B

Table 4. History of changes.

Version	Publication date	Change
1.0	15/07/2024	Initial version.

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