Journal of Building Engineering 96 (2024) 110542

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Industry 5.0, towards an enhanced built cultural heritage conservation practice

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ARTICLE INFO

Keywords:
Industry 5.0
Human-centrism
Resilience
Sustainability
Built cultural heritage environment
Conservation
Systematic literature review

ABSTRACT

The rise of Industry 4.0 has led to a rapid increase in digitalization and industrial operations. However, it has recently been deemed insufficient in fulfilling European objectives for 2030. In response, and to counteract the unintended negative consequences triggered by Industry 4.0, Industry 5.0 has been introduced. The purpose of this article is to shed light on how the architecture, engineering, construction, management, operation, and conservation industry can adapt and better prepare to embrace novel Industry 5.0 principles and enabling technologies, ultimately resulting in enhanced conservation practices for the built cultural heritage environment. To achieve this, a systematic literature review was conducted following the PRISMA methodology. The principal results of this article highlight the work of different conservation professionals and our views on the potential of Industry 5.0 for enhancing conservation practices. Major conclusions indicate that artificial intelligence and digital twins are the two most studied technologies in the field. Sustainability is broadly discussed throughout the analyzed literature, whereas resilience and human centrism require further research and implementation efforts to achieve a holistic Industry 5.0 adoption. The significant scientific novelty of this work lies in the comprehensive scope of the review in terms of principles and enabling technologies, with a particular emphasis on heritage buildings. Thus, it is valuable for conservation practitioners seeking best practices, for policymakers as it suggests ways to encourage the adoption of novel technologies and principles in conservation, and for researchers as it highlights gaps and stimulates further paths of research and innovation.

1. Introduction

Heritage can be broadly classified into two main categories: natural and cultural. A third category, known as mixed heritage, refers to heritage formed by the combination of elements from both natural and Cultural Heritage (CH). Natural heritage encompasses "*natural features, geological and physiographical formations and delineated areas that constitute the habitat of threatened species of*

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https://doi.org/10.1016/j.jobe.2024.110542
Received 17 May 2024; Received in revised form 17 August 2024; Accepted 20 August 2024

animals and plants and natural sites of value from the point of view of science, conservation, or natural beauty. It includes private and publicly protected natural areas, zoos, aquaria and botanical gardens, natural habitat, marine ecosystems, sanctuaries, reservoirs, etc." [1]. CH is traditionally divided into intangible and tangible. Intangible CH refers to "*the practices, representations, expressions, knowledge, and know-how, transmitted from generation to generation within communities, created and transformed continuously by them, depending on the environment and their interaction with nature and history*" [2]. Tangible CH can be broadly separated into movable and immovable assets. Within the scope of this work, the term "*Built Cultural Heritage Environment*" (BCHE) refers to immovable CH formed by man-made structures, buildings, sites, infrastructure, landmarks, and spaces with historical, architectural, artistic, cultural, scientific, or social significance and value [3].

The United Nations Educational, Scientific and Cultural Organization (UNESCO) promotes global cultural equality and heritage conservation. By adopting the 1972 World Heritage Convention, UNESCO Member States become responsible for identifying, protecting, conserving, and presenting the world's heritage [4]. With the adoption of the Venice Charter in 1964 [5], and other significant documents that followed and complemented it [6–9], the foundational principles and guidelines for the practice of BCHE conservation were established. One of the most widely accepted conservation principles is multidisciplinary collaboration. Thus, different stakeholders of the Architecture, Engineering, Construction, Management, Operation, and Conservation (AECMO&C) industry, along with experts from various other fields, such as history, archaeology, sociology, etc., are required to collaborate to achieve a holistic and appropriate conservation of the BCHE. Unfortunately, the successful completion of this task is complicated by the vulnerability of the invaluable assets of the BCHE to different human-induced, socio-economic, and natural hazards [10], especially in the face of climate change [11].

On the other hand, the conservation of the BCHE holds the potential to contribute to efforts in combating climate change. In 2015, the United Nations (UN) adopted the 2030 Agenda for Sustainable Development and 17 Sustainability Development Goals (SDG) aimed at achieving present and future peace and prosperity for both humans and the planet [12]. This policy framework recognizes in SDG 11, Target 11.4, that safeguarding CH contributes to making cities and human settlements inclusive, safe, resilient, and sustainable [13]. Thus, efforts to preserve the BCHE are both required and desirable [14]. Regrettably, as highlighted by the UN Emissions Gap Report 2022 [15], inadequate action has been taken on the global climate crisis. A rapid transformation in the energy supply, manufacturing, transport, and buildings sectors is needed if the goals of the Paris Agreement [16] are to be achieved. Such transformation is also endorsed by the European Union (EU) and encouraged by the European Green Deal [17], primarily through its creative and interdisciplinary New European Bauhaus initiative [18].

Significant efforts have been made to improve the conservation of the BCHE through the advancement and adoption of novel technologies. In recent years, the conservation practice has benefited from some of the technological progress developed during Industry 4.0, such as improved museum conservation enabled by Digital Twins (DT) [19], enhanced experiences through extended reality application to cultural places [20], better public engagement in the conservation of heritage buildings through 3D reconstructions via drone [21], remote sensing techniques applied to archaeology conservation [22], and optimized bridge management and operation through the use of advanced anomaly detection algorithms [23]. While the vision of Industry 4.0 has driven digitalization and increased productivity, it has been deemed inadequate to achieve European development goals by 2030 [24]. The technology-centered approach of Industry 4.0 is considered insufficient to address the challenges posed by the current context of the climate crisis and socio-economic inequalities. As a result, a novel Industry 5.0 paradigm has emerged. Industry 5.0 is primarily based on three foundational principles: i) human-centrism, ii) resilience, and iii) sustainability. The recognized enabling technologies of this new transformative vision include a) individualized human-machine-interaction, b) bio-inspired technologies and smart materials, c) DT and simulation, d) data transmission, storage, and analysis technologies, e) Artificial Intelligence (AI), and f) technologies for energy efficiency, renewables, storage, and autonomy [25]. Despite being recently adopted (2020), Industry 5.0 fundamental concepts and technologies have been explored [26–28], innovative implementation frameworks have been suggested [29–31], and applications in fields such as manufacturing [32], education [33], data privacy [34], and wind energy infrastructure [35] have been conducted. Unfortunately, there is a gap among conservation practitioners and AECMO&C industry stakeholders regarding the implementation of Industry 5.0 principles and enabling technologies, particularly in the conservation of the BCHE.

Therefore, the objective of this work through the elaboration of a Systematic Literature Review (SLR) is to gather, synthesize, and analyze state-of-the-art knowledge and information to determine how Industry 5.0 principles and enabling technologies can contribute to improving built CH conservation practices, unveil current gaps, and highlight potential future developments and opportunities in the field. To this end, the proposed SLR aims to answer the following question.

- How can the AECMO&C industry adapt and be better prepared to embrace novel Industry 5.0 principles and enabling technologies ultimately leading to enhanced practices in built CH conservation?

There are several high-quality and valuable systematic literature reviews (SLRs) already published in the literature. For example, the outstanding SLR conducted by Vuoto et al. [36] focuses on the Digital Twin (DT) concept and its implementation in the field of Built Cultural Heritage (BCHE) conservation, while the insightful work by Ikudayisi et al. [37] addresses how a series of integrated practices throughout the project delivery lifecycle (i.e., design, construction, management/operation, decommissioning) could lead to the adoption of Industry 5.0. The novelty of this work is justified by its distinction from these existing SLRs. Unlike the SLR on DTs by Vuoto et al. this work encompasses all the enabling technologies identified by the EU within the specific scope of Industry 5.0. Additionally, it differs from Ikudayisi et al.'s SLR on conventional architecture, engineering, and construction by focusing specifically on the built environment with cultural heritage value. These specific elements embedded in the proposed research question underscore the novelty and scientific rigor of the work presented in this manuscript.

The outline of the manuscript is organized as follows: Section 2 contains a short description of the methodology followed to conduct the SLR and details on the process conducted to analyze the obtained bibliographic data. In particular, the protocol followed to conduct the SLR has been previously peer reviewed and approved, full details can be consulted in the corresponding reference [38]. Section 3 presents the results obtained from the work performed in terms of performance analysis, science mapping, and narrative synthesis, along with appropriate discussions on the findings, and finally, Section 4 contains the conclusions drawn from this work where we have aimed at answering in a summarized manner the research question at the hearth of this SLR.

2. Materials and methods

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement methodology [39,40] was adopted to conduct the SLR presented in this work. The protocol adopted has been published and made publicly available [38], along with the corresponding protocol [41] and search strategy [42] checklists. This SLR has been reported in the Open Science Framework (OSF) website under project number jn834 [43] and preregistered in the OSF Registries website under registration number gpy6b [44].

2.1. Bibliometric analysis methodology

The bibliographic data from the identified records after deduplication has been processed through a bibliometric analysis. This is a quantitative methodology that allows for the description of publication patterns and the extraction of meaningful insights from large quantities of data [45]. By examining the number of publications and frequency of citations, among other parameters, it is possible to identify emerging research trends in a field, collaboration opportunities, and publication patterns, and explore the structure of the published literature. Two main approaches of bibliometric analysis were adopted in this work, namely, science mapping and performance analysis. The performance analysis was executed by querying, filtering, and sorting the bibliographic database obtained after deduplication. The information from 872 records is presented in terms of publications per year, documents per country, and keyword occurrence. The keyword occurrence analysis was conducted using both "Author Keywords" and "Index Keywords", as provided by Scopus. The science mapping analysis was performed using the VOSviewer v1.6.18 software. The mapping was focused on analyzing the co-authorship relationships in terms of countries, as well as the co-occurrence relationships between keywords (both author and index keywords). This allowed the visualization of the interconnections of core concepts and topics within the area of interest. Further information about the detailed creation and characteristics of the VOSviewer maps can be found elsewhere [46].

2.2. SLR methodology

The quality of SLR heavily relies on the adopted protocol and search strategy used to identify relevant records. However, these two elements are seldom reported adequately. The rationale, hypothesis, and planned methods of this SLR are based on the PRISMA-P [47,48], and its search strategy follows the recommendations of the PRISMA-S extension [49]. Due to its wide coverage of the literature, high-quality content and advanced data extraction capabilities, Scopus [50] was selected as the database to conduct the search strategy of this SLR. The eligibility criteria consisted of including peer-reviewed records published as articles, conference papers, book chapters, or reviews in journals, conference proceedings, books, or book series. The search was limited to the subject areas of Computer Science, Engineering, Business Management and Accounting, Decision Sciences, Social Sciences, Economics Econometrics and Finance, Energy, Environmental Science, Materials Science, Arts and Humanities, and Multidisciplinary. Only those records published from 2020 to 2024, written in English, and containing the following keywords of interest (and similar terms, namely: human-centrism and human-centric, etc.) as part of the record's title, abstract, or keywords, were initially eligible.

- Human-centrism
- Resilience
- Sustainability
- Human-centric solutions
- Human-machine-interaction
- Bio-inspired technologies
- Smart materials
- Digital twins
- Cyber safe data
- Artificial intelligence.
- Energy efficiency
- Trustworthy autonomy
- Built Cultural Heritage Environment
- Conservation.

Three different Search Queries (SQ) were run implementing the specified eligibility criteria and combining the various keywords of interest. The full SQs are presented in Table 1, where * represents the wild character, AND and OR are Boolean operators, "⋅" is used to group individual words into multi-word keywords and (⋅) is used to group several terms.

The search strategy adopted was created specifically for this SLR and no update method was used as the final manuscript was planned to be completed shortly after the search had been performed. The search was conducted on Feb. 16, 2024. A total of 907 records were identified and a Findable, Accessible, Interoperable, and Reusable (FAIR) [51] bibliographic database was created with

Table 1
Full SQs run in Scopus to identify relevant records.

#	Full query
SQ1	TITLE-ABS-KEY (“industry 5.0″ AND (heritage OR conservation)) AND PUBYEAR > 2019 AND PUBYEAR < 2025 AND (LIMIT-TO (SRCTYPE, “j") OR LIMIT-TO (SRCTYPE, “p") OR LIMIT-TO (SRCTYPE, “k") OR LIMIT-TO (SRCTYPE, “b")) AND (LIMIT-TO (DOCTYPE, “ar”) OR LIMIT-TO (DOCTYPE, “cp”) OR LIMIT-TO (DOCTYPE, “ch”) OR LIMIT-TO (DOCTYPE, “re”)) AND (LIMIT-TO (SUBJAREA, “COMP”) OR LIMIT-TO (SUBJAREA, “ENGI”) OR LIMIT-TO (SUBJAREA, “BUSI”) OR LIMIT-TO (SUBJAREA, “DECI”) OR LIMIT-TO (SUBJAREA, “SOCI”) OR LIMIT-TO (SUBJAREA, “ECON”) OR LIMIT-TO (SUBJAREA, “ENER”) OR LIMIT-TO (SUBJAREA, “ENVI”) OR LIMIT-TO (SUBJAREA, “MATE”) OR LIMIT-TO (SUBJAREA, “ARTS”) OR LIMIT-TO (SUBJAREA, “MULT”)) AND (LIMIT-TO (LANGUAGE, “English”))
SQ2	TITLE-ABS-KEY ((human-centr* OR resilien* OR sustainab*) AND (“cultural heritage” AND conservation)) AND PUBYEAR > 2019 AND PUBYEAR < 2025 AND (LIMIT-TO (SRCTYPE, “j") OR LIMIT-TO (SRCTYPE, “p") OR LIMIT-TO (SRCTYPE, “k") OR LIMIT-TO (SRCTYPE, “b")) AND (LIMIT-TO (DOCTYPE, “ar”) OR LIMIT-TO (DOCTYPE, “cp”) OR LIMIT-TO (DOCTYPE, “ch”) OR LIMIT-TO (DOCTYPE, “re”)) AND (LIMIT-TO (SUBJAREA, “COMP”) OR LIMIT-TO (SUBJAREA, “ENGI”) OR LIMIT-TO (SUBJAREA, “BUSI”) OR LIMIT-TO (SUBJAREA, “DECI”) OR LIMIT-TO (SUBJAREA, “SOCI”) OR LIMIT-TO (SUBJAREA, “ECON”) OR LIMIT-TO (SUBJAREA, “ENER”) OR LIMIT-TO (SUBJAREA, “ENVI”) OR LIMIT-TO (SUBJAREA, “MATE”) OR LIMIT-TO (SUBJAREA, “ARTS”) OR LIMIT-TO (SUBJAREA, “MULT”)) AND (LIMIT-TO (LANGUAGE, “English”))
SQ3	TITLE-ABS-KEY ((human-centr* OR human-machin* OR bio-inspired OR “smart material*" OR “digital twin*" OR “cyber safe” OR “artificial intelligence” OR “energy efficien*" OR “trustworthy autonom*") AND (“cultural heritage” AND conservation)) AND PUBYEAR > 2019 AND PUBYEAR < 2025 AND (LIMIT-TO (SRCTYPE, “j") OR LIMIT-TO (SRCTYPE, “p") OR LIMIT-TO (SRCTYPE, “k") OR LIMIT-TO (SRCTYPE, “b")) AND (LIMIT-TO (DOCTYPE, “ar”) OR LIMIT-TO (DOCTYPE, “cp”) OR LIMIT-TO (DOCTYPE, “ch”) OR LIMIT-TO (DOCTYPE, “re”)) AND (LIMIT-TO (SUBJAREA, “COMP”) OR LIMIT-TO (SUBJAREA, “ENGI”) OR LIMIT-TO (SUBJAREA, “BUSI”) OR LIMIT-TO (SUBJAREA, “DECI”) OR LIMIT-TO (SUBJAREA, “SOCI”) OR LIMIT-TO (SUBJAREA, “ECON”) OR LIMIT-TO (SUBJAREA, “ENER”) OR LIMIT-TO (SUBJAREA, “ENVI”) OR LIMIT-TO (SUBJAREA, “MATE”) OR LIMIT-TO (SUBJAREA, “ARTS”) OR LIMIT-TO (SUBJAREA, “MULT”)) AND (LIMIT-TO (LANGUAGE, “English”))

all the bibliographic information of the records identified at this stage [52]. The deduplication process was conducted automatically in EndNote [53] software and this resulted in the removal of 35 records. Deduplication, filtering, screening, and eligibility assessment of all those records were carried out following the PRISMA flow diagram for systematic reviews as presented in Fig. 1.

All remaining records after deduplication were screened by two independent reviewers based on title, abstract, and keywords. Disagreements on the selection process were resolved by a third reviewer who ultimately decided on the selection or rejection of the corresponding record. All records remaining from the screening process were sought for retrieval, and those found were assessed for inclusion based on their entire content. Qualitative data were extracted from the included records related to the three principles (human-centrism, resilience, sustainability) and enabling technologies (human-machine-interaction, bio-inspired technologies, and smart materials, DT and simulation, data transmission, storage, and analysis technologies, AI, and energy efficiency and trustworthy autonomy) of Industry 5.0 applied within a built CH conservation context. Finally, the relevant information extracted from the included records was qualitatively summarized in a narrative synthesis as the findings were characterized by heterogeneity.

3. Results and discussion

The results from the identification, screening, and inclusion process are presented in Fig. 1. From the 907 initially identified records, 35 were removed as they were duplicates. Thus, 872 records were screened based on their title, abstract, and keywords. Of these, 717 records were excluded by humans as they were deemed irrelevant to the scope of this SLR. As a result, 155 records were sought for retrieval, but 10 of them were neither found online nor accessible by any of the authors of this work. Therefore, only 145 records were assessed for inclusion based on their full content. At this stage, records were excluded mainly due to five reasons. Three records were rejected due to their overall low quality. Four more records were not included as they did not deal with any of the enabling technologies of Industry 5.0.20 additional records were excluded as the main application of the technologies discussed in them was not related to the area of BCHE. The most common reason for rejection at this stage was that records did not deal in detail with any of the principles of Industry 5.0, leading to the exclusion of 36 records. Furthermore, four records were grouped within the area of underwater CH. Although they presented interesting research findings on the use of robots for the enhanced conservation of this type of heritage, they were ultimately also excluded as their extrapolation to the BCHE was not straightforward. Finally, the total number of records included in the SLR was 78.

3.1. Performance analysis

After the automatic deduplication process was successfully conducted and manually verified, the performance analysis took place using the bibliographic data from the remaining 872 records. The number of papers published each year is presented in Fig. 2. As previously indicated, the time frame of this SLR spans from 2020, when the EU first released the Industry 5.0 concept [54], to Feb. 16, 2024, when the search was conducted. From Fig. 2, it can be observed that the number of publications has been rising on a linear trend from 2020 until 2023. Moreover, if the number of publications from the first month and a half of 2024 is extrapolated, it would suggest that the total number of publications for this year could almost reach 300 records. This linear growth indicates an increasing interest in the area by stakeholders in the AECMO&C industry. This growth is not as significant as in other fields such as sustainability [55], innovation [56], or manufacturing [57], which exhibit an exponential trend. This may be due to the low flexibility and slow adaptation of novel technologies and procedures in the field of conservation. This cautious behavior is, to some extent, justifiable by the respect of one of the main principles adopted in the Venice Charter for the conservation and restoration of monuments and sites [5]. Article 10 of the Charter mandates thorough testing and validation of any new material or technology used for the intervention on the built CH to avoid, regrettably common, maladaptation and unsympathetic interventions.

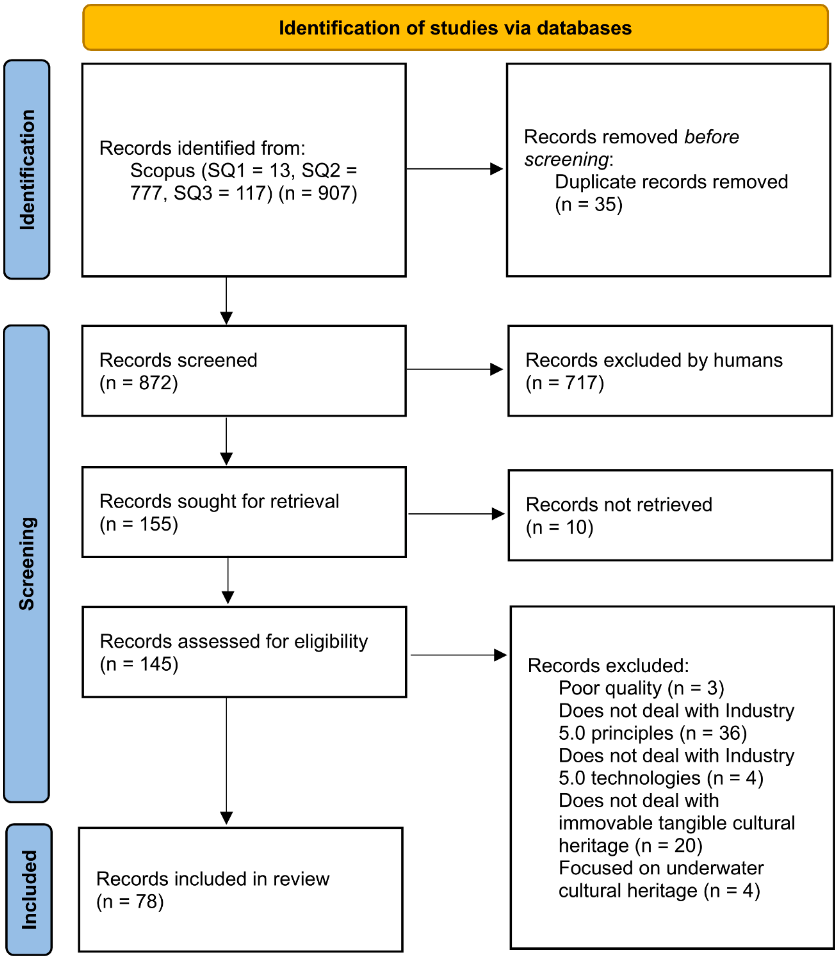


Fig. 1. Number of records identified, screened, and included in the SLR, adapted from the PRISMA 2020 flow diagram [39].

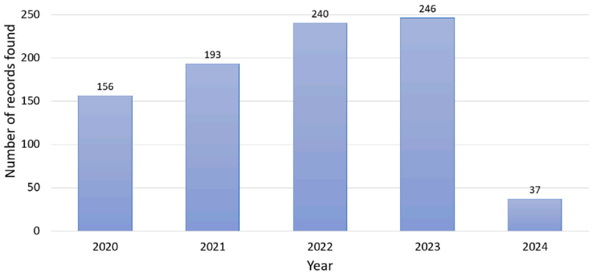


Fig. 2. Number of records found per year after deduplication.

The most common keywords found are presented in Fig. 3. Of particular interest for this SLR are the keywords related to the principles and enabling technologies of Industry 5.0. Thus, it can be observed that “Sustainability” appeared 134 times (“Sustainable Development”, a closely related keyword, was the second most common keyword with a total of 194 appearances.), whereas “Artificial Intelligence” appeared on 38 records. This observation is not surprising as these two keywords are considered “hot topics” among the research community and span multiple fields. However, it is noticeable that the remaining principles (i.e., human-centrism and resilience) are absent among the most common keywords. This signals the need to expand research efforts in those two directions to achieve a balanced adaptation and implementation of the novel Industry 5.0 paradigm in the conservation of the BCHE. Similarly, the remaining enabling technologies require further development and adoption to match the performance of AI among stakeholders of the AECMO&C industry. Nonetheless, research on AI must also progress, as it has the potential to enhance the performance of other Industry 5.0 enabling technologies, as discussed for the case of DT [23], human-machine-interaction (e.g., cobots) [58], the development of smart materials [59], and energy efficiency [60], to name a few.

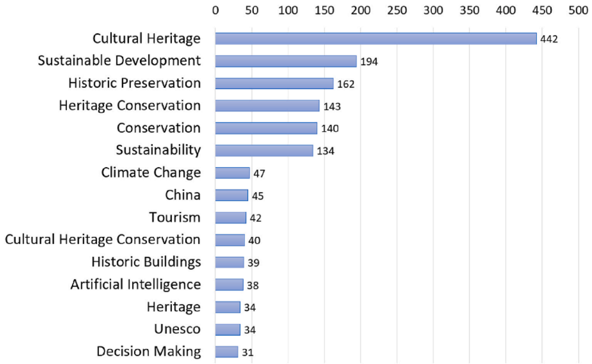
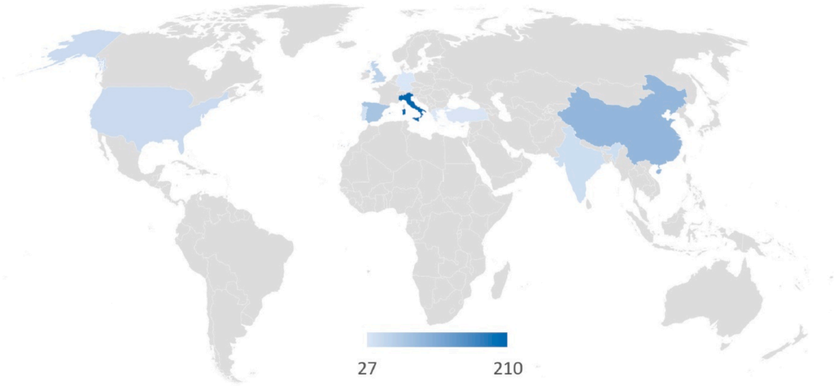
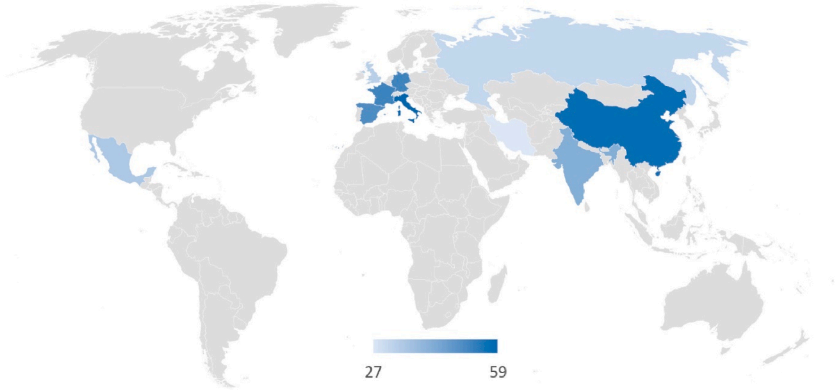


Fig. 3. The most common keywords found among the deduplicated records.

The top ten countries with the highest number of records identified are listed in Fig. 4a. It is unsurprising to see Italy as the country with the highest number of records (210), as this is the nation with the largest number of UNESCO World Heritage Sites (59 at the time this paper is being written [61], see Fig. 4b) and has historically played a leading role in the field of BCHE conservation. Other Western countries with an important number of records within the scope of this SLR are Spain (78), the United Kingdom (55), and the United States (45). The records published in China (98), where the importance of the conservation of heritage buildings has been widely acknowledged [62], and India (41) help to balance the representation between the West and the East in the set. By comparing the two maps presented in Fig. 4 it can also be said that neither Russia, Iran, Mexico, or France (which are among the top ten countries with the most UNESCO World Heritage sites) appear among the top ten countries with the highest number of records identified on this SLR. This may be a sign of a lack of investment and general interest in the national policies of those countries (among many other geopolitical issues outside the scope of this work) toward the conservation of their BCHE. Unfortunately, no country from Latin America, Africa, or Southeast Asia made it onto the list, which evidences the well-known inequality gap between the Global North and the



(a)



(b)

Fig. 4. (a) Top ten countries with higher number of records identified after deduplication and (b) Top ten countries with the most UNESCO World Heritage sites (as per July 17, 2024).

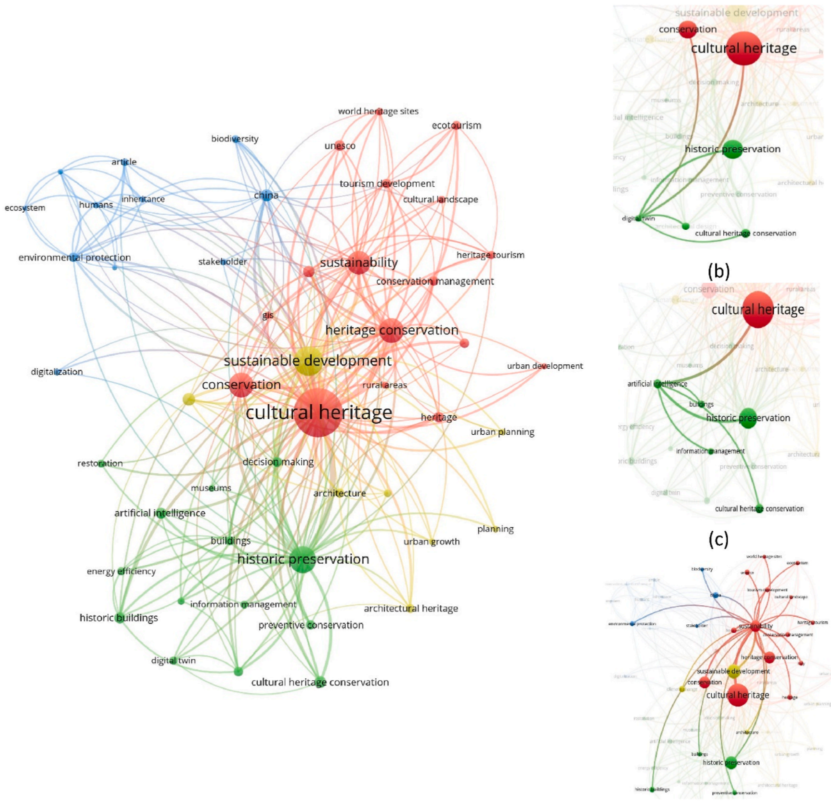
Global South (with China and India being the noted exceptions). Further research needs to be developed locally in these countries to promote sustainable development and improve conservation practices within these rich heritage nations. Successful local implementation of Industry 5.0 principles and enabling technologies in the Global South could help to move beyond development aid and contribute to ending the existing center-periphery imbalances [63].

3.2. Science mapping

A keywords co-occurrence map was created to complement the information presented in Fig. 3 and to better understand the interrelationships between keywords (see Fig. 5 a). The information is grouped into four clusters, each identified by a specific color. The first cluster contains all keywords shown in red, including "cultural heritage" (the most common keyword with 442 occurrences) and other related terms such as "heritage conservation" and "sustainability". The second cluster includes the terms colored in green and has "historic preservation" (162 occurrences) as its main item. The third and fourth clusters are colored orange and blue respectively. The main element of the former is "sustainable development" (194 occurrences), whereas the latter does not seem to have a single principal component, but it appears to center around "environmental protection" (30 occurrences) and similar concepts (i.e., "biodiversity", "ecosystem", etc.). Thus, most keywords are grouped within the first two clusters and are closely related to topics on heritage and conservation. On the other hand, the remaining clusters are more related to environmental aspects.

Of special interest are the three isolated nodes presented in Fig. 5, two of which correspond to Industry 5.0 enabling technologies, namely, "digital twin" (b) and "artificial intelligence" (c), while the third one pertains to one of its core principles, "sustainability" (d). It can be observed that both "artificial intelligence" and "digital twin" co-occur with the main elements of clusters one and two ("cultural heritage" and "historic preservation") as well as with "cultural heritage conservation" and a few other keywords. Besides, "sustainability" has a broader presence in the literature and is widely linked to various topics and ideas. In addition to being connected to the main elements of the first three described clusters, it is also interlinked with various subjects ranging from "eco-tourism" and "biodiversity" to "cultural landscape". It is worth noting the absence of the other two Industry 5.0 principles among the mapped keywords, which is evidence of a lack of research on those two topics among stakeholders of the AECMO&C industry working on BCHE conservation. Similar observations could be made regarding the missing enabling technologies on the co-occurrence map, as with the absent principles, also in line with the discussion in Section 4.1.

Fig. 6 presents the co-authorship map, featuring the top 50 countries with the highest number of records. Countries are similarly clustered into four groups and differentiated by color, as in the keywords co-occurrence map. In Fig. 6 it can be observed that three of the clusters are centered around European countries. Specifically, the yellow cluster around Italy (210 records), the blue cluster cen-



(a) (b) (c) (d)

Fig. 5. Keywords co-occurrence map: (a) Overall view, (b) "digital twin", (c) "artificial intelligence", and (d) "sustainability.

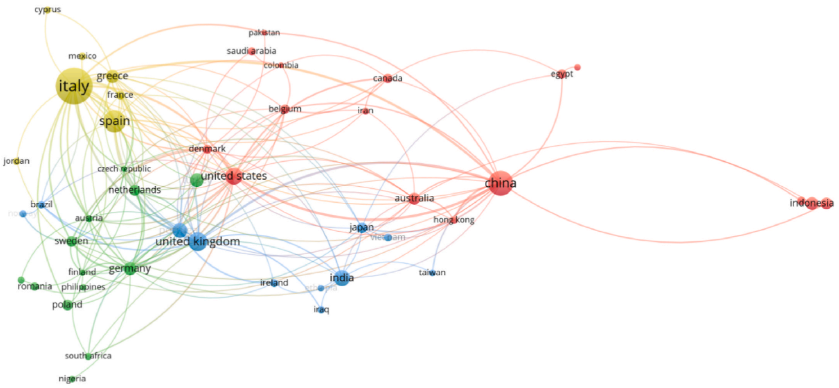


Fig. 6. Countries co-authorship map, where countries are clustered by color into four different groups. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

tered on the United Kingdom (55 records), and the green group mainly represented by Germany (28 records). The last cluster, colored in red, gathers countries from all remaining continents, with China being the country with the highest number of records among the elements of this fourth cluster (98 documents). It is interesting to see in this map the presence of countries from the Global South such as Mexico and Brazil from Latino America, Egypt and South Africa from Africa, and Indonesia and the Philippines from Southeast Asia, among others. This could be particularly valuable for researchers working in these countries to identify colleagues working in countries with higher research output in the field and potentially create new connections and collaborations.

3.3. *Integration of findings and contextualization of results*

The information from the 78 included records of this SLR has been processed, compared, and analyzed through a narrative synthesis approach. The records have been organized, and will be presented, primarily into two large groups: those papers dealing mainly with Industry 5.0 principles, and those papers presenting and discussing in detail one or several of the identified enabling technologies of this novel paradigm (see Fig. 7). Thus, four papers were assigned to the human-centrism principle [20,64–66], five papers to the resilience principle [67–71], and finally, the sustainability principle had the higher number of papers, a total of 21 [72–92]. On the other hand, with regards to Industry 5.0 enabling technologies, only three records dealt with human-centric solutions and human-machine-interaction [93–95], the content of two more papers was mainly focused on bio-inspired and smart materials [96,97], 16 papers were grouped within the real time-based DT and simulation category [23,98–112], and 16 records were gathered under the topic of cyber safe data transmission, storage, and analysis [113–128]. Finally, seven and four records were clustered within the categories of AI [129–135] and energy efficiency and trustworthy autonomy [136–139], respectively.

3.3.1. *Human-centrism*

The human-centrism principle is perhaps the most distinguishing feature of Industry 5.0 compared to its predecessor, Industry 4.0. This principle aims to re-introduce the lost dimension of humanity, thus, centering Industry 5.0 not around a dominating techno-deterministic rationale, but around humans and a human-deterministic approach [54]. Within this humanistic point of view, Industry 5.0 emphasizes the combination of human and technological skills for the benefit of both the industry and its workers. It is not about technology replacing humans, but working alongside them to create safer, more enjoyable, and ergonomic work environments where people can thrive. This approach has the potential to stimulate creativity, the creation of new roles, and the improvement of digital skills in the AECMO&C industry.

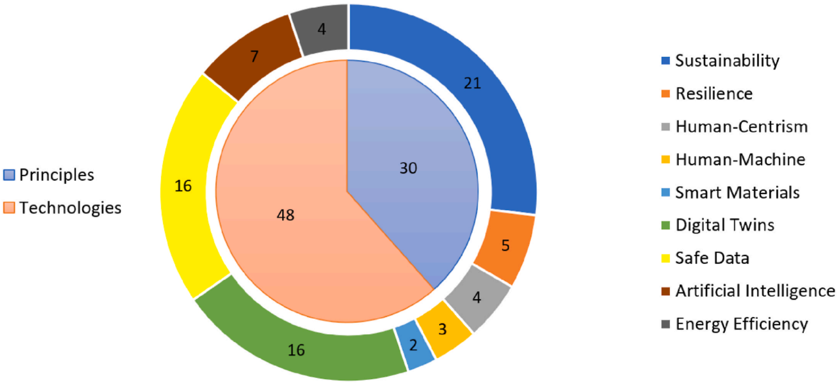


Fig. 7. Classification of included records for their presentation in the narrative synthesis.

Focusing on the conservation of the BCHE, Murphy et al. [20] proposed a human-centered manifesto, guiding the inclusion of smart digital immersion in CH spaces. Their manifesto proposes 13 principles to which every human-centered digital immersive system must adhere, namely: Fairness, Inclusivity, Respect and Empathy, Education, Flexibility, Protection, Personalization, Support, Symbiosis, Empowerment, Legacy, Dynamic, and Transcendence. After analyzing the adherence of five digital CH projects, they concluded that Education was their primary focus. Support, Personalization, and Respect and Empathy were also highly valued, whereas a lack of Fairness was observed. In another work by Murphy et al. [64], the use of blockchain and non-fungible tokens to support the documentation and the transfer of digital information within the CH field is discussed from a human-centric perspective. Another example of human-centric research is the ethical framework developed by Pansoni et al. [65]. Such a framework aims to avoid undermining the role of the different professionals in conservation when AI is adopted. They proposed 6 core principles to prevent cultural and historical biases, underrepresentation of minorities, problems related to reproduction and authenticity, as well as the uneven distribution of economic resources, the allocation of responsibility, and the protection of privacy. Such framework encompasses the principles of Explainability, Cultural Continuity, Economic Accessibility, Right to be Forgotten, Reliability, and Centrality. The authors argue that if ethical risks emerge, the application of the proposed framework may provide a trustworthy application of AI in the conservation of the BCHE.

Another form of integrating the human-centric principle within built CH conservation practices is by adopting participatory approaches and involving citizens in the decision-making process (bottom-up approach). This is a philosophy shift in conservation which has gained strength in recent years. An increasing number of professionals in the field are moving from a material-preservation approach towards a more value-preservation practice, influenced by ideas related to circular governance and heritage communities [140]. Li et al. [66] have surveyed residents of Nara, Japan, to investigate their willingness to pay for projects on the Adaptive Reuse of Cultural Heritage (ARCH), which represents a value-preservation approach. Through a contingent valuation method and an ordered logistic regression model, their results show that three-quarters of the population were willing to pay for ARCH projects. Such a high percentage of acceptance was linked to the heritage value awareness of the people along with a strong feeling of place attachment among Nara inhabitants.

3.3.2. Resilience

The term “resilience” has been given many definitions over the years. A broadly adopted one defines resilience as “*The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions*” [141]. In the field of BCHE, resilience is viewed as a value, and it is often attributed to those assets that have survived for hundreds or thousands of years. Nevertheless, Jones [67] has raised the concern about a lack of a solid critical theoretical foundation. He argues that, although this concept has been widespread and broadly coined by different conservation professionals, it has been diffusively adopted and used barely as a “buzzword” or a “fuzzy concept” leading in some cases to consider this important principle as “useless”. The author suggested further work is needed in terms of conceptual level critiques, development of a forward-looking approach, and consideration of counter-current research ideas to fully profit from the concept of resilience in the BCHE conservation practices.

Immovable CH assets are susceptible to disasters that, based on their duration, can be classified as rapid- and slow-onset disasters. The first refers to rapid catastrophic events, namely, terrorist acts, wars, earthquakes, floods, etc., whereas the latter is mainly represented by the long-term effects of climate change, which persist over time and lead to adverse conditions [68]. Various research efforts aim to enhance the resilience of BCHE against both. These efforts include the digitalization of CH documentation, particularly for minor or inaccessible heritage sites, as proposed by Maietti [69]. Rufian Fernandez et al. [70] emphasized the importance of safe and efficient documentation of endangered CH using digital tools, which involves local populations during the recovery stage, thus connecting to the human-centrism principle. Additionally, Di Ludovico [71] suggested smarter reconstruction of historic city centers through local community mapping processes and the implementation of novel technologies aligned with Industry 5.0.

3.3.3. Sustainability

Among the three principles of Industry 5.0, sustainability is the most extensively discussed in the literature (as previously noted in Section 4.1). Even records presented within the human-centrism, resilience, and the different enabling technologies subsections discuss sustainability aspects to some extent. Therefore, it is important to note that the papers discussed in this subsection focus primarily on sustainability itself, rather than on the application of specific technologies or methodologies. Subsequent discussions cover topics such as social media, tourism, materials, and manufacturing processes within this sustainability context.

Social media is nowadays recognized as a potential tool to facilitate and promote collaboration between different stakeholders. Liang et al. [72] have explored how sustainability could be influenced within a BCHE conservation scenario by different social media platforms. They conclude that social media could be especially important to achieve sustainability if used as a civic engagement tool, particularly within the context of the Historic Urban Landscape approach [142]. The discussion is further enriched by Liang [73], who identified the different ways in which the use of social media can contribute to achieving sustainable CH management. Primarily, the author identified social media as a people-centered approach where heritage can be shared (collective memory), and culture can be expressed (storytelling). The author also warns that in cases where social media tools are mainly used for dissemination, this could lead to an elitist, instead of a democratic, situation. From another perspective, Foroughi et al. [74] have investigated how the information shared on social media, by both locals and tourists, can be used to better understand the cultural significance of built CH assets and channel conservation efforts towards what is perceived as to have the most significant value.

Tourism is an important component of the economy in places with a rich BCHE as people are attracted by the beauty, history, and significance of such assets. Unfortunately, if not managed adequately, overtourism can cause serious issues both for the CH itself (e.g., anthropological degradation) and for the local communities (e.g., gentrification), against the principles of the International Cultural Tourism Charter [143]. By implementing several novel technologies, de la Plata et al. [75] aimed at developing a sustainable management model of tourism for the city of Merida, Spain. Their proposal not only digitized the cultural sites of interest but also presented the information to tourists clearly and attractively, ensuring its universalization without compromising the conservation stage of the assets. Similarly, Liu et al. [76] explored the relationship between BCHE and sustainable tourism practice. Their approach was based on the use of digital economy technologies and directly linked these two concepts to the attainment of UN SDGs.

Further efforts to enhance sustainability practices within the conservation of the BCHE turn around participatory approaches. Bizzarri et al. [77], utilizing a multi-agent participatory methodology involving a variety of stakeholders (conservation professionals, a national government agency, local workers, and university students), managed to increase the interest of the local community and invited the inhabitants of the surrounding villages to play an active role in the conservation of their CH. The interventions conducted during this project were based on the use of traditional skills using local and sustainable materials, thus ensuring adequate long-term maintenance of a case study site in Oman. Another empirical case study based on citizen engagement was developed in India by Billore [78]. The main contribution of this diverse and inclusive initiative, which involved citizens, students, funding agencies, and industry companies, was the establishment of a culture-based sustainability model. This model ultimately led to increased responsibility toward collective cultural consumption, enhanced synergistic participation, and improved community knowledge. Nared and Bole [79] implemented a similar participatory approach, this time from a southeastern European perspective, involving various stakeholders such as policymakers, conservation professionals, researchers, and the general public interested in the topic, to articulate a culture-based development model. Their findings showed that the unique and characteristic heritage values of the region could promote sustainable development if adequately used as branding tools, motivation factors, and means for community empowerment and strengthening of local identity. In a different study, the local community, visitors, NGOs, and governmental bodies were involved in a participatory exercise to develop the necessary policies to achieve a sustainable conservation practice in a rural village in Turkey [80]. The methodology was mainly influenced by a social sustainability component and successfully ensured the preservation of the village's integrity. A key element in the successful implementation of any participatory approach is the so-called “stakeholder consciousness” as defined by Aureli and Del Baldo [81]. Such state of awareness may be attained through the active involvement of multiple agents in the co-design and co-implementation of heritage revitalization initiatives and CH policies. Moreover, they suggest that participatory approaches and methodologies must aim at establishing lasting forms of collaboration; otherwise, long-term results may not be achieved.

Several researchers have placed a distinct focus on sustainability, exploring the topics of circularity and adaptability of the BCHE. These efforts have been fostered since 2020, the same year in which Industry 5.0 was presented, among other initiatives, by the EU Renovation Wave Strategy [144]. In this context, Foster and Saleh [82] approached the topic from an economic perspective, adopting a circular city model and an ARCH perspective. Hence, they introduced a novel index that combines both concepts so that city managers, conservation professionals, and other relevant stakeholders can have a systematic method to measure the investment opportunity within a European context. The index was developed by following a composite indicators and scoreboards tool and considered 15 different indicators encompassing aspects of cultural stock, environmental stewardship, and socioeconomic demographics. The top three ranked cities were: 1) Paris, 2) London, and 3) Berlin, and all top 50 cities were in Western and Central Europe, which indicates that further dissemination of ARCH and the circular city model is needed among Eastern European cities. Also from an economic perspective, Ost and Saleh [83] have discussed comprehensively the value chain of activities (creation, conservation, dissemination, fruition, and engagement) related to the BCHE conservation. They proposed an assessment process to estimate the potential codestruction of values in situations confronting the reuse of existing immovable CH assets or their demolition to build new ones. Such methodology accounts for the loss of authenticity and integrity, consideration of negative side-effects, and opportunity costs, enabling decision-makers to prove the feasibility and viability of ARCH projects. The notion that existing built CH assets are highly sustainable is strongly supported by the findings of Redden and Crawford [84]. Based on the results obtained after an extensive literature review, they claimed that historic buildings are high environmental performers. The inadequate assessment of such valuable assets in certain studies can be attributed to the limitations of narrowly focused methodologies. These methodologies often overlook important indicators such as resource depletion, material waste, and pollution. Bosone et al. [85] have examined the significant role of digital technologies in the adoption of circularity and ARCH models. Among their findings, they emphasize the emergence of two novel concepts: “digital commons”, defined as a series of open resources, freely used, and democratically shared, developed and managed by people, and “prosumers”, a concept that combines the roles of users (consumers) and producers. Finally, Pintossi et al. [86] explored the challenges posed by ARCH in a local case study of Salerno, Italy, using a participatory approach (another example of the previously discussed methodology). Moreover, after thorough discussions, including topics such as knowledge production and management, participation valorization, and cooperation, they proposed a series of plausible solutions aimed at decision and policymakers to promote the adoption of ARCH for achieving sustainable development based on BCHE conservation.

It is recognized that novel technologies used on the conservation of the BCHE are seldomly developed for purposes specific to the field but rather adopted from other areas of research after being broadly tested and validated. This is the case argued by Vega-Bosch et al. [87], who conducted a study of cryogenics (dry ice blasting), a technology widely used in the aerospace and industrial sectors, and its possible uses on the conservation of immovable CH assets. Their findings show that adopting cryogenics would lead to economically feasible and sympathetic interventions, enhancing the sustainability of conservation practices. Cryogenics would replace the use of toxic chemical substances currently in use, provide a safer work environment for conservators, and contribute to the achievement of five UN SDGs (SDGs 7, 8, 9, 12, and 13). Another recently adopted technology in the field of BCHE conservation is additive manufacturing. Altadonna et al. [88] have evaluated through a Life Cycle Analysis, the environmental impact of two 3D printing techniques used to produce built CH asset models, namely Computed Numerical Control and Fused Deposition Modeling. The authors concluded that, although Fused Deposition Modeling produces lower material waste and environmental impact, as well as lower initial investment costs for the case study conducted, Computed Numerical Control may be more sustainable for large-volume production scales due to its flexibility and versatility in processing a wider range of materials.

Other records identified in this SLR dealing with the sustainability principle comprise a green conservation framework based on specifically defined targets, tools, and tasks proposed by Shehata et al. [89]; a preventive conservation methodology rooted in digital technologies and work indicators developed by Zhou et al. [90]; a heritage city sustainability index suggested by Saleh et al. [91] to measure the contribution that the integration of built CH assets may have on the achievement of sustainable cities; and the capacity building program presented by Reina Ortiz et al. [92] to train professionals of the AECMO&C industry to adequately deal with the conservation of the BCHE within a Latin American context. Furthermore, regarding the training of professionals of the AECMO&C industry, it is worth noting the recent initiative launched by the EU for the creation of the New European Bauhaus Academy on skills for sustainable construction with innovative materials [145]. Its purpose is to accelerate the up-skilling and re-skilling in the AECMO&C industry workforce to support the transition to a regenerative bio-economy and circular system of material reuse transition. This presents an opportunity for various stakeholders involved in the conservation of the BCHE to benefit from, by developing learning activities that incorporate Industry 5.0 principles and enabling technologies, and by participating in the envisioned network and collaborative platform. Other funding opportunities can also be found at the national level, such as the "*Piano Transizione 5.0*" launched by the Italian government.

3.3.4. Human-centric solutions and human-machine-interaction

Human-centric solutions and human-machine-interaction technologies within the context of Industry 5.0 are envisioned as tools to support humans and enhance human innovation and creativity through the help of machine capabilities [54]. Among the various means to achieve this aim are multilingual speech and gesture recognition; technologies for tracking physical and mental employee stress; collaborative robots (cobots); augmented, virtual, and mixed realities; exoskeletons; and human cognitive capabilities enhancements through the development of AI-based decision support systems. All these technologies have experienced an important development in recent years and are commonly referred to as human-in-the-loop within the Industry 4.0 paradigm [146–148]. However, within the novel vision of Industry 5.0, which aims to place humans at the core of all activities, what is now sought is better described as a symbiosis between human and technological components [149].

In such context, Nota and Petraglia [93] have proposed a novel three-tiered situational awareness model for the conservation of heritage buildings. It consists of the perception of environmental elements at the first level, situation comprehension at the second level, and a future status projection at the last level. Their model aims at enhancing human monitoring, controlling, and management capabilities of the BCHE by means of a cyber-physical assisted decision support system. Promising results were obtained after applying the proposed model to the study case of an Italian palace and the model is now used as the base of other projects on the conservation of historic villages. Furthermore, Zhang et al. [94] suggested a framework for the creation of a built CH metaverse to enhance cultural tourism, asset management, and conservation. Such metaverse would consist of elements grouped within five distinct dimensions, namely linearity (music, folk stories, audio guides), planarity (paintings, blueprints, photographs), space (buildings, bridges, ruins), time (live performances, kinematic art, living towns), and context (history, culture, religion). This methodology has been tested by the authors on the creation of a metaverse experience for the Eight Immortals located at Haq Par Villa, Singapore, which was originally designed to promote Taoism. On the other hand, Salonia [95] has explored the role of robotics and augmented reality, among other digital technologies, in the conservation of the BCHE. Although the author recognizes the significant improvement of technology applications in the field of BCHE conservation, it is argued that such improvements are unfortunately not always accompanied by lower costs, process simplifications, or an increase in awareness of the identity value of the studied cases. All these gaps need to be addressed in future research to achieve a successful adaptation of the AECMO&C industry to adopt Industry 5.0 enabling technologies.

3.3.5. Bio-inspired and smart materials

Bio-inspired technologies and developments in smart materials within the field of BCHE conservation are primarily envisioned for application in consolidation interventions. Wang et al. [96] identified and classified a series of bio-inspired materials used in the consolidation of timber assets. Biomass materials derived from natural sources are most suitable for strengthening indoor timber components. Nanocomposites, including nanoparticles, nanocellulose, and other polymers, are mainly used to neutralize wood acidity, serve as protective coatings, and enhance the internal structure of timber. Finally, the use of green bionic materials and polymerization technologies is especially suitable to enhance timber strength and flexibility while remaining compatible with the original wood material. From another perspective, Rossi and Bournas [97] have described various smart sensing materials capable of enhancing the monitoring of built CH assets. Novel applications of fiber optic sensors, piezoelectric sensors, and self-sensing materials are among the latest advances in this area. Particularly interesting for the conservation of the BCHE is the novel concept of "smart bricks", which are electrically conductive and piezoresistive, thus being capable of monitoring strains and detecting damage on in-plane loaded structures. Within this context, the recent "revival" of earth-based and vernacular architecture building technologies and materials has experienced an increased interest from the research community based on their potential to achieve sustainable construction practices [150–152].

3.3.6. Real time-based DT and simulation

Among the various stakeholders in the AECMO&C industry, there is a particular interest in the development and implementation of DT. DT is a concept that involves both the physical asset and the creation of a virtual copy of it, along with an interconnection component that links both assets and can track the physical asset performance in real time [98]. This allows, among other functionalities, to spot possible problems before they escalate, thereby enhancing safety and reducing maintenance costs [153]. There is a unified viewpoint and agreement on the use of these DTs in the design, construction, management, operation, and decommissioning of built environment assets. Such interest has also increased in recent years among professionals dealing with the conservation of built CH assets [99]. Jiménez Rios et al. [23] identified a suitable Industry 4.0 DT framework for built CH assets based on an As-Is Historical Asset Information Model (AI-HAIM, in this concept the word "Asset" replaces the word "Building" commonly used in the Historical Building Information Modeling (HBIM) [154] approach to extend the proposed framework to various kinds of built CH assets, i.e., bridges, aqueducts, canals, etc.). This AI-HAIM must contain interoperable data, geometry, finite element, and data-driven modules ("digital asset") and be linked to its real-world counterpart through a multi-metric asset health monitoring system. That system should continuously produce data on the asset's structural, environmental, and operational conditions ("physical asset"). The authors have also identified as major challenges in creating Industry 4.0 DT the lack of clear guidelines for creating macro-DT integrating individual asset models, and the absence of FAIR benchmark databases suitable for DT prototyping development and validation [155,156]. Another major gap is the lack of interoperability among different software and data used in the DT model generation, as clearly highlighted by Sajjadian [157], who warns against the disruptive effect that this unsolved issue may have during Industry 5.0 implementation.

A key stage in the creation of DT is to accurately capture the geometry of the physical assets to generate a high-fidelity virtual replica. Krukowski and Vogiatzaki [100] presented novel 3D modeling approaches based on photogrammetric methods and on automatically acquired images by an unmanned aerial vehicle, commonly known as drone. The resulting models achieved a high degree of accuracy with their proposed approach, and the simplicity of the required devices means that highly skilled professionals are not needed to implement the proposed methodology. Stanga et al. [101] also used drones photogrammetry, complemented with total station measurements, laser scanner, and terrestrial photogrammetry, to acquire the geometric data of the Claudius Anio Novus aqueduct in the Tor Fiscale Park, Rome, Italy. The highly accurate data obtained was then processed to generate HBIM and virtual reality models, integrating the heritage context of the asset and providing an enriched user experience to visitors.

Nevertheless, DT technology is still in its early stages of development and implementation within the BCHE conservation field. Some recent attempts at creating DT include the European case studies of an Italian church elaborated by Marra et al. [102] (selected because its features and size were considered of low-to-moderate complexity, ideal for a first implementation test), the Cathedral of San Mateo Quadriportico, Salerno, Italy, by Falcone et al. [103] following a graph-based management approach, the conservation works conducted in the façade of the Church of Santa Maria di Nazareth, Venice, Italy, by Rocca et al. [104], the model of the pulpit of Giovanni Pisano, in Pistoia, Italy, within the context of the CHARMING PISTOIA project by Monchetti et al. [105], the implementation of a virtual technical tour approach by Bruno et al. [106] on two different built CH assets in the south of Italy, the villa Zingali Tetto, Catania, Italy, by La Russa and Santagati [107], and more recently, the impressive case study of Santa Maria in Trastevere, Rome, Italy, where Ippolito et al. [108] implemented various methods for the digital documentation of this important UNESCO world heritage asset. Nguyen et al. [109] have digitized and created HBIM, virtual and augmented reality models of the Hung King Temple, Ho Chi Minh, Vietnam, to promote digital tourism and make CH available through technology. All these examples are limited to the creation of HBIM models, but actual DTs are expected to be achieved after future work is completed.

Other topics discussed within the DT approach applied to the conservation of the BCHE include the need to identify and validate the veracity or the original virtual replica of a physical asset and the training of conservation professionals. Darwish and Hassanien [110] proposed the use of blockchain technology to credit, identify, and authenticate original DT of built CH assets, thus ensuring adequate rights management and ownership value preservation. In turn, Borucka and Parrinello [111] presented the vision for the creation of a new international Master's programme (120 ECTs on 2 years) to educate professionals on technologies related to Industry 5.0 enabling technologies while fostering a sensitive approach towards built CH conservation. Their work was developed within the VREA consortium, which involved seven higher education institutions from Europe, America, and Asia, as well as other third-party collaborators. As concluded by Haddad [112] after conducting a review of visual digital technologies and their application on documentation, conservation, and monitoring of the BCHE, there is an urgent need for new seminars, workshops, and guidelines targeting the various AECMO&C industry stakeholders and multidisciplinary professionals involved in BCHE conservation.

3.3.7. *Cyber safe data transmission, storage, and analysis*

The enabling technologies of the transformative Industry 5.0 vision either generate large amounts of data (e.g., DT) or rely on what is known as big data (e.g., AI) to function adequately [158]. The nature of such data is complex and multimeric, obtained from a wide range of devices and monitoring strategies. The big data scenario is further complicated when dealing with large-scale built CH assets, like in the study case reported by Chen et al. [113]. These authors studied a portion of the Great Wall in China, known as the Badaling Great Wall, considered the most prominent section of the Great Wall with several kilometers of length. Very-high resolution multi-temporal spotlight TerraSAR-X data were collected from satellite-based Earth observations from 2019 to 2020. Another example of big data on the conservation of the BCHE is discussed by Gawronek and Noszczyk [114], who conducted terrestrial laser scanning during the intervention works for the redevelopment of a historic granary in Poland. The surveying campaign of this relatively modest asset, which took place between 2017 and 2019, resulted in a hefty amount of data points, later used to generate an HBIM model and enhance the decision-making process along the redevelopment project. Moreover, as discussed by Lerario [115], internet of things technologies have the potential to generate vast amounts of tracking and behavioral data from users of built CH assets, which can later be processed and utilized to provide better visiting experiences and enhance management and conservation strategies. To deal with the challenge of adequately handling vast amounts of data, several research efforts have proposed the creation of various digital platforms, information systems, and information management approaches.

Digital platforms operate on a democratic principle, involving users in the collection, support, extraction, exchange, connection, interaction, and social relationship of their resources. The participatory nature of digital platforms is particularly attractive in the field of BCHE conservation, given the universal value and common interest in CH. Longo et al. [116] have reviewed the CH digital platforms proposed by three research projects, namely, INCEPTION [117–119], ROCK [120,121], and IDEHA, created to act as repositories, processing, and visualization hubs of open and interoperable multiformat data obtained from various sources. Their results show the usefulness of all platforms as decision and monitoring support systems and as a means for the creation of collaborative stakeholders' networks. Another recently developed digital platform for the conservation of the BCHE is SyPEAH [122]. Based on open-source modules and a WebGIS approach, this platform was created to manage the UNESCO world heritage site assets of the "*Parco Archeologico del Colosseo*", Rome, Italy, although not openly available to be adopted in other case studies. Conversely, Moreno et al. [123] have launched a free and publicly available platform capable of assisting in the definition of strategies for BCHE conservation. The Art-Risk 3.0 platform consists of three modules: interface, GIS database, and AI engine. It implements a fuzzy-logic inference system to identify threat levels and degrees of vulnerability of built CH assets, classifying them according to a risk index and enabling optimal resource allocation to conduct preventive conservation. Unfortunately, the scope of this tool is limited only to a Spanish context. Finally, Doan et al. [125] have proposed the creation of a smart platform through participatory processes to improve community access and raise awareness of the values and advantages of conserving French colonial villas in Hanoi, Vietnam.

In alignment with the digitalization trend observed in recent years in the management and conservation of CH, Mateus et al. [124] proposed the creation of an open-access information system specialized on historical and military Portuguese heritage. The development of this innovative tool is based on a back-end LAMP solution and a conventional front-end implementation (HTML, CSS, and Javascript). Still in the prototype stage, this information system is envisioned as a sustainable and inclusive management model that would benefit the safeguarding of CH while promoting social and economic development. Other national initiatives for the collection, preservation, and dissemination of CH through information systems are identified by Gireesh Kumar [126], who also highlights the lack of a national information system in the Indian context. Among the more important examples mentioned by Gireesh Kumar are Romania, Finland, Qatar, Ireland, and Uganda. At a European level, the recently created information system for the conservation of CH is called Europeana, which "*provides cultural heritage enthusiasts, professionals, teachers, and researchers with access to Europe's digital cultural heritage*". At the moment of writing this article (April 2024), Europeana had more than 31 million images, almost 25 million documents, 1.2 million audio files, 366 thousand videos, and 5105 3D objects available for consultation.

The creation of innovative digital platforms and information systems, coupled with the digitalization of CH, resulting in the emergence of what is called "digital heritage", presents a challenge for effectively managing the vast amount of digital information generated. Within this context, various authors have developed novel information management strategies to adequately deal with digitized assets. Masciotta et al. [127], through the HeritageCare project, suggested an integrated digital-based methodology for the preventive conservation of built CH assets. Their approach encompasses the stages of information documentation, registration, and management while directly involving the asset owners in the conservation process. The HeritageCare methodology envisions the implementation of a multi-level information system that increases in complexity based on the preventive conservation requirements of different assets. Accordingly, it provides correspondingly complex functionalities, with the generation of an HBIM model being one of the products of the more advanced service level proposed. Furthermore, Korro Bañuelos et al. [128] explored a series of conservation case studies to define a conceptual framework for effectively managing information within the context of BCHE conservation. They concluded that despite the increased number of information and digital tools among conservation professionals, further efforts are needed to address interoperability issues among the various tools developed, as well as to enhance their outreach and reusability. Alternative ontological data sharing and management approaches applied to the conservation of the BCHE have been proposed by Moyano et al. [159].

3.3.8. AI

AI is a pervasive technology with applications in areas as diverse as religion education [160], medicine [161], and mathematics and logic [162], to name a few. In the field of BCHE conservation, AI is used both as an independent tool, as well as an enabler for the correct operationalization of other digital technologies [129]. Tzima et al. [130] applied machine learning algorithms to process the large quantities of satellite synthetic-aperture radar and optical data collected during the monitoring of historic cities in Cyprus, namely, Nicosia and Limassol. Both random forest and maximum likelihood, which are supervised machine learning algorithms, were used to generate a landcover classification at the pixel level and to detect changes in the urban development of the studied cities. Their work would enable local authorities to adequately preserve the BCHE from rapid uncontrolled urbanization and climate change impacts.

Other direct applications of AI for the conservation of the BCHE found in this SLR are related to damage detection and the so-called scan-to-BIM technologies. Alexakis et al. [131] implemented a pyramid scene parsing network, which is a deep learning encoder/decoder structure particularly effective in performing segmentation tasks, to analyze Infrared Thermography images and detect damages caused by raising damp in two important built CH case studies in the Middle East (the Holy Aedicule of the Holy Sepulcher, Jerusalem, and the Msma'a historic building, Hebron). Rodrigues et al. [132] used a Convolutional Neural Network (CNN) based on Residual Network (ResNet) architectures to detect various pathologies (i.e., cracks, efflorescence, stains, among others) in historic buildings. Furthermore, their workflow also included the interpolation of the detected damages within an HBIM model to assist on the decision-making process for the conservation of built CH assets. Their methodology was tested and validated in the case study of the Church of Santa Casa da Misericordia, Aveiro, Portugal, although relatively low F1 scores were obtained due to the small size of the photographic database used to train the CNN. Finally, Masini et al. [133] conducted a dimensionality reduction analysis (Kernel Principal Component Analysis, Isometric Mapping, and t-distributed Stochastic Neighbor Embedding) to study the structural response of the world-famous Brunelleschi's Dome, at "*Santa Maria del Fiore*" Cathedral, Florence, Italy,. These authors investigated the feasibility of several CNN and recurrent neural networks to predict the medium and long-term structural behavior of the dome. Their results showed that, while all three dimensionality reduction techniques could detect seasonal periodicity on the behavior of the monitored cracks in the dome, KPCA was the technique that provided a lower overall residual variance ratio, thus deemed to be the more effective approach. On the other hand, Croce et al. [134] used random forest algorithms to assist in the semantic segmentation of point clouds for the automatic construction of HBIM models, whereas Matrone and Martini [135] exploited the freely available "*Architectural Cultural Heritage*" database to train an enhanced Dynamic Graph CNN modified with 3D features to conduct semantic segmentation of point clouds achieving overall accuracy above 84 %. The semantic segmentation approaches presented by both authors hold the promise of reducing the HBIM model generation time from hours to only minutes, significantly boosting the productivity of conservation professionals.

3.3.9. Energy efficiency and trustworthy autonomy

To keep the rise in global temperatures below 1.5 °C, as outlined in the Paris Agreement [16], a net-zero policy has been extensively encouraged at the international level by the UN. Net zero is defined as "*cutting carbon emissions to a small amount of residual emissions that can be absorbed and durably stored by nature and other carbon dioxide removal measures, leaving zero in the atmosphere*" [163]. As one of the main factors contributing to human greenhouse gas emissions is the direct energy consumption in buildings [15], several technological attempts aimed at improving the energy performance of built CH assets have been developed. These efforts are intended to support the global goal of achieving net-zero emissions by 2040 in developed countries and by 2050 in developing countries [164].

Piselli et al. [136] developed an integrated modeling and simulation framework based on HBIM for the energy retrofitting of built CH assets with a renewable geothermal heating, ventilation, and air conditioning system. The authors implemented the framework in a medieval complex in Italy, resulting in considerable benefits, namely 73 % less heating energy and 69 % CO_2 emissions cut while keeping the same occupancy conditions and comfort levels. Also based on an HBIM approach, Moyano et al. [137] demonstrated the benefits of monitoring microclimate data and energy parameters for improving decision-making within the field of built CH conservation. In turn, Massafra et al. [138] integrated building performance simulation tools within an HBIM environment to assess the intervention benefits in terms of thermal demand in a series of listed modern buildings in Italy. Their multi-criteria analysis (annual heat energy demand, investment costs, lifecycle costs, payback period, and upgrade level) enables the comparison and optimization of different energy performance improvement strategies. From another point of view, Lucchi [139] has conducted an extensive review on the integration of photovoltaic systems as energy retrofitting measurements of built CH assets. Photovoltaics, whose main advantages are reliability, modularity, scalability, versatility, low maintenance costs, and peak shaving, is a technology with the potential to contribute towards achieving net-zero emissions. Lucchi's work has identified relevant policies, recommendations, and design criteria required for adequate and sympathetic integration of photovoltaic panels on historic buildings. According to the author, three main levels of integration need to be respected, namely aesthetic, technical, and energetic. The main criteria to be considered include panel color, reflectivity, concealment, shape, and location within the built CH asset.

4. Conclusions

The work presented in this manuscript fulfills the aims of the envisaged systematic literature review. These aims include gathering, synthesizing, and analyzing state-of-the-art knowledge and information to determine how Industry 5.0 principles and enabling technologies can contribute to improving built cultural heritage environment conservation practices. Furthermore, it has generated critical insights into the current applications and future potential of Industry 5.0 principles and enabling technologies in enhancing conservation practices.

To address the research question posed in this systematic literature review—specifically, how the AECMO&C industry can adapt and better prepare to embrace Industry 5.0 principles and enabling technologies to enhance practices in built cultural heritage (CH) conservation—the following key strategies have been identified.

- Leveraging human-centric frameworks: The AECMO&C industry can adapt by effectively utilizing human-centric frameworks that prioritize ethical considerations and promote participatory, value-centered conservation practices. This approach ensures that the human element remains at the forefront, aligning with the principles of Industry 5.0.
- Emphasizing resilience: Resilience, one of the core principles of Industry 5.0, should be adopted to systematically analyze and implement strategies that enhance the industry's ability to withstand both rapid- and slow-onset disasters. This is increasingly relevant in the context of digitalization, where resilience is becoming integral to safeguarding cultural heritage.
- Advancing sustainable practices: Significant progress in areas such as social media, tourism, materials, and manufacturing processes reflects the industry's evolution toward sustainability. For example, the use of smart bricks for structural monitoring, along with innovative data generation, processing, and exploitation strategies, are recognized as groundbreaking approaches that contribute to more sustainable conservation practices.
- Harnessing artificial intelligence: AI has emerged as a powerful tool, both as an independent technology and as an enabler for other digital innovations. Its implementation can significantly boost productivity among professional conservators, facilitating more efficient and effective conservation efforts.

These strategies collectively represent the means by which the AECMO&C industry can adapt to and prepare for the integration of Industry 5.0 principles and enabling technologies, ultimately leading to improved conservation practices in built cultural heritage. These conclusions are based on the bibliographic evidence found through the rigorous SLR conducted and presented in the structure narrative synthesis of this manuscript.

The SLR also highlights several gaps in the current understanding and application of Industry 5.0 principles and technologies. Adoption has been conservative, with a need for better integration of sustainability and AI with other technologies. There is also a geographical inequality in Industry 5.0 research and implementation, suggesting that Global South countries could benefit from early adoption and collaborations with leading stakeholders. Training for conservation professionals requires further collaboration, particularly through regional and national initiatives.

Further challenges were identified in creating digital twins, including software interoperability issues, lack of guidelines for macro-digital twins, and the absence of suitable databases for digital twin development and validation. Additionally, data safety technologies like blockchain need further exploration to ensure authorship recognition and proper conservation of digital heritage assets. The increasing energy demands of Industry 5.0 technologies also present a critical challenge that extends beyond the AECMO&C industry and would require broader multi-stakeholder consensus to be tackled.

The novelty of this work lies in its comprehensive review of Industry 5.0 principles and technologies, with a focus on BCHE. It is valuable for conservation practitioners seeking best practices, policymakers promoting new technologies, and researchers exploring gaps for further innovation. The practical outcomes are expected to enhance conservation practices through resilience strategies, smart material retrofitting, real-time monitoring, and community engagement in decision-making. In conclusion, while Industry 5.0 offers significant potential for conservation, addressing these gaps and challenges is essential to fully realize its benefits.

Funding

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No. 101066739. The APC was funded by Oslo Metropolitan University under the Open Access Agreement between Norway and Elsevier.

CRediT authorship contribution statement

Alejandro Jiménez Rios: Writing – review & editing, Writing – original draft, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Margarita L. Petrou:** Writing – original draft, Methodology, Investigation, Data curation. **Rafael Ramirez:** Writing – original draft, Methodology, Investigation, Data curation. **Vagelis Plevris:** Writing – review & editing, Supervision, Funding acquisition. **Maria Nogal:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Alejandro Jiménez Rios would like to acknowledge the support provided by the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM) through one of its distinguished ICCROM Fellowships, assigned to him and for hosting him at the ICCROM Headquarters in the city of Rome, Italy, during the period when the presented work was conducted.

Data availability

The datasets generated for this study can be found in the Zenodo repository: https://doi.org/10.5281/zenodo.10671411

Abbreviations

PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
CH	Cultural Heritage
BCHE	Built Cultural Heritage Environment
UNESCO	United Nations Educational, Scientific and Cultural Organization
AECMO&C	Architecture, Engineering, Construction, Management, Operation, and Conservation
UN	United Nations
SDG	Sustainability Development Goals
EU	European Union
DT	Digital Twins
AI	Artificial Intelligence
SLR	Systematic Literature Review
OSF	Open Science Framework
SQ	Search Queries

FAIR	Findable, Accessible, Interoperable, and Reusable
ARCH	Adaptive Reuse of Cultural Heritage
AI-HAIM	As-Is Historical Asset Information Model
HBIM	Historical Building Information Modeling
CNN	Convolutional Neural Network

References

[1] UNESCO, Convention concerning the protection of the world cultural and natural heritage, URL: https://whc.unesco.org/archive/convention-en.pdf, 1972.
[2] UNESCO, Convention for the safeguarding of the intangible cultural heritage, 2003 URL: https://ich.unesco.org/doc/src/15164-EN.pdf, 2003.
[3] UNESCO WHC, World heritage information kit, URL: https://whc.unesco.org/en/activities/567/, 2008.
[4] UNESCO WHC, Operational guidelines for the implementation of the world heritage convention, URL: https://whc.unesco.org/en/guidelines/, 2016.
[5] ICOMOS, International Charter for the Conservation and Restoration of Monuments and Sites, ICOMOS, Venice, 1964. https://www.icomos.org/images/DOCUMENTS/Charters/venice_e.pdf.
[6] ICOMOS, Guidelines for the Analysis, Conservation and Structural Restoration of Architectural Heritage, ICOMOS, Victoria Falls, Zimbabwe, 2003. https://iscarsah.files.wordpress.com/2023/01/part-ii-e28093-guidelines.pdf.
[7] ICOMOS, Principles for the Analysis, Conservation and Structural Restoration of Architectural Heritage, Vicoria Falls, Zimbabwe ICOMOS, 2003. https://iscarsah.files.wordpress.com/2014/11/iscarsah-principles-english.pdf.
[8] ICOMOS, *The Australia ICOMOS Charter for Places of Cultural Significance*. 2013, Burra, Australia: ICOMOS. https://openarchive.icomos.org/id/eprint/2145/.
[9] ICOMOS, The Nara document on authenticity, ICOMOS, Nara, Japan: 1994. https://whc.unesco.org/archive/nara94.htm.
[10] UNESCO, State of conservation of world heritage properties, URL: https://whc.unesco.org/en/soc/, 2014.
[11] UNESCO, Policy document on the impacts of climate change on world heritage properties, URL: https://whc.unesco.org/en/CC-policy-document/, 2006.
[12] United Nations, Transforming our world: the 2030 Agenda for sustainable development, URL: https://sdlugs.un.org/sites/default/files/publications/2125203020Agenda20for20Sustainable20Development20web.pdf, 2015.
[13] United Nations, Rescuing SDG 11 for a resilent urban planet, URL: https://uis.unesco.org/sites/default/files/documents/sdg_11_synthesis_report_2023_v11_0_4.pdf, 2023.
[14] European Commission, Strengthening cultural heritage resilience for climate change, URL: https://op.europa.eu/en/publication-detail/-/publication/4bfcf605-2741-11ed-8fa0-01aa75ed71a1/language-en/format-PDF/source-search, 2022.
[15] United Nations, Emissions gap Report 2022, URL: https://www.unep.org/resources/emissions-gap-report-2022, 2022.
[16] United Nations, The Paris Agreement, URL: https://unfccc.int/process-and-meetings/the-paris-agreement, 2015.
[17] European Commission, The European green deal, URL: https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF, 2019.
[18] European Commission, New European Bauhaus, URL: https://new-european-bauhaus.europa.eu/system/files_en?file=2021-01/New-European-Bauhaus-Explained.pdf, 2023.
[19] W. Luther, et al., Digital twins and enabling technologies in museums and cultural heritage: an overview, Sensors 23 (3) (2023), https://doi.org/10.3390/s23031583.
[20] C. Murphy, P.J. Carew, L. Stapleton, *A human-centred systems manifesto for smart digital immersion in Industry 5.0: a case study of cultural heritage.* AI and Society, https://doi.org/10.1007/s00146-023-01693-2, 2023.
[21] Q. Li, et al., Single drone-based 3D reconstruction approach to improve public engagement in conservation of heritage buildings: a case of Hakka Tulou, J. Build. Eng. 87 (2024) 108954, https://doi.org/10.1016/j.jobe.2024.108954.
[22] A. Alviz-Meza, et al., Bibliometric analysis of fourth industrial revolution applied to heritage studies based on web of science and scopus databases from 2016 to 2021, Heritage Science 10 (1) (2022) 189, https://doi.org/10.1186/s40494-022-00821-3.
[23] A. Jiménez Rios, V. Plevris, M. Nogal, Bridge management through digital twin-based anomaly detection systems: a systematic review, Frontiers in Built Environment (2023), https://doi.org/10.3389/fbuil.2023.1176621.
[24] European Commission, Industry 5.0: a transformative vision for Europe, URL: https://research-and-innovation.ec.europa.eu/knowledge-publications-tools-and-data/publications/all-publications/industry-50-transformative-vision-europe_en, 2022.
[25] European Commission, Industry 5.0 : towards a sustainable, human-centric and resilient European industry, URL: https://data.europa.eu/doi/10.2777/308407, 2021.
[26] D. Mourtzis, J. Angelopoulos, N. Panopoulos, Operator 5.0: a survey on enabling technologies and a framework for digital manufacturing based on extended reality, Journal of Machine Engineering 22 (1) (2022) 43–69, https://doi.org/10.36897/jme/147160.
[27] I. Taj, N.Z. Jhanjhi, Towards industrial revolution 5.0 and explainable artificial intelligence: challenges and opportunities, International Journal of Computing and Digital Systems 12 (1) (2022) 285–310, https://doi.org/10.12785/ijcds/120124.
[28] U. Asad, et al., Human-centric digital twins in industry: a comprehensive review of enabling technologies and implementation strategies, Sensors 23 (8) (2023), https://doi.org/10.3390/s23083938.
[29] C. Yang, et al., Extended reality application framework for a digital-twin-based smart crane, Appl. Sci. 12 (12) (2022), https://doi.org/10.3390/app12126030.
[30] P. Fraga-Lamas, et al., Mist and edge computing cyber-physical human-centered systems for industry 5.0: a cost-effective IoT thermal imaging safety system, Sensors 22 (21) (2022), https://doi.org/10.3390/s22218500.
[31] J. Lehmann, et al., The anatomy of the internet of digital twins: a symbiosis of agent and digital twin paradigms enhancing resilience (not only) in manufacturing environments, Machines 11 (5) (2023), https://doi.org/10.3390/machines11050504.
[32] C. Li, et al., An AR-assisted Deep Reinforcement Learning-based approach towards mutual-cognitive safe human-robot interaction, Robot. Comput. Integrated Manuf. 80 (2023), https://doi.org/10.1016/j.rcim.2022.102471.
[33] K. Eriksson, et al., Applying Digital Twin Technology in Higher Education: an Automation Line Case Study, IOS Press BV, 2022, https://doi.org/10.3233/ATDE220165.
[34] A. Sasikumar, et al., Blockchain-based trust mechanism for digital twin empowered Industrial Internet of Things, Future Generat. Comput. Syst. 141 (2023) 16–27, https://doi.org/10.1016/j.future.2022.11.002.
[35] X. Chen, et al., A human-cyber-physical system toward intelligent wind turbine operation and maintenance, Sustainability 13 (2) (2021) 1–10, https://doi.org/10.3390/su13020561.
[36] Vuoto, A., M.F. Funari, and P.B. Lourenço, Shaping Digital Twin Concept for Built Cultural Heritage Conservation: A Systematic Literature Review. Int. J. Architect. Herit.: p. 1-34 https://doi.org/10.1080/15583058.2023.2258084.
[37] A.E. Ikudayisi, et al., Integrated practices in the architecture, engineering, and construction industry: current scope and pathway towards industry 5.0, J. Build. Eng. 73 (2023) 106788, https://doi.org/10.1016/j.jobe.2023.106788.
[38] A. Jiménez Rios, et al., Industry 5.0 concepts and enabling technologies, towards an enhanced conservation practice: systematic literature review protocol [version 1; peer review: 2 approved], Open Research Europe 4 (75) (2024), https://doi.org/10.12688/openreseurope.17505.1.
[39] M.J. Page, et al., The PRISMA 2020 statement: an updated guideline for reporting systematic reviews, BMJ 372 (2021) n71, https://doi.org/10.1136/bmj.n71.
[40] M.J. Page, et al., PRISMA 2020 explanation and elaboration: updated guidance and exemplars for reporting systematic reviews, BMJ 372 (2021) n160, https://doi.org/10.1136/bmj.n160.
[41] A. Jiménez Rios, et al., Industry 5.0 concepts and enabling technologies, towards an enhanced conservation practice: systematic literature review protocol checklist, https://doi.org/10.5281/zenodo.10877563, 2024.

[42] A. Jiménez Rios, et al., Industry 5.0 concepts and enabling technologies, towards an enhanced conservation practice: systematic literature review search strategy checklist, https://doi.org/10.5281/zenodo.10875793, 2024.

[43] A. Jiménez Rios, et al., Industry 5.0 concepts and enabling technologies, towards an enhanced conservation practice, URL: https://osf.io/jn834/, 2024.

[44] A. Jiménez Rios, et al., Industry 5.0 concepts and enabling technologies, towards an enhanced conservation practice, https://doi.org/10.17605/OSF.IO/GPY6B, 2024.

[45] R.N. Broadus, Toward a definition of "bibliometrics", Scientometrics 12 (5) (1987) 373–379, https://doi.org/10.1007/BF02016680.

[46] N.J. van Eck, L. Waltman, Visualizing bibliometric networks, in: Y. Ding, R. Rousseau, D. Wolfram (Eds.), Measuring Scholarly Impact: Methods and Practice, Springer International Publishing, Cham, 2014, pp. 285–320, https://doi.org/10.1007/978-3-319-10377-8_13.

[47] D. Moher, et al., Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement, Syst. Rev. 4 (1) (2015) 1, https://doi.org/10.1186/2046-4053-4-1.

[48] L. Shamseer, et al., Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015: elaboration and explanation, BMJ Br. Med. J. (Clin. Res. Ed.) 349 (2015) g7647, https://doi.org/10.1136/bmj.g7647.

[49] M.L. Rethlefsen, et al., PRISMA-S: an extension to the PRISMA statement for reporting literature searches in systematic reviews, Syst. Rev. 10 (1) (2021) 39, https://doi.org/10.1186/s13643-020-01542-z.

[50] Elsevier, Scopus (2024). https://www.elsevier.com/products/scopus. (Accessed 4 June 2024).

[51] M.D. Wilkinson, et al., The FAIR Guiding Principles for scientific data management and stewardship, Sci. Data 3 (1) (2016) 160018, https://doi.org/10.1038/sdata.2016.18.

[52] A. Jiménez Rios, et al., Bibliographic Dataset for the Systematic Literature Review on Industry 5.0 Concepts and Enabling Technologies, towards an Enhanced Conservation Practice, Zenodo, 2024, https://doi.org/10.5281/zenodo.10671411.

[53] The EndNote Team, EndNote 20, EndNote (2023). https://endnote.com/.

[54] European Commission, Enabling Technologies for Industry 5.0 : results of a workshop with Europe's technology leaders, URL: https://data.europa.eu/doi/10.2777/082634, 2020.

[55] M.I. Baig, E. Yadegaridehkordi, Industry 5.0 applications for sustainability: a systematic review and future research directions, Sustain. Dev. 32 (1) (2024) 662–681, https://doi.org/10.1002/sd.2699.

[56] B. Afzal, X. Li, A.B. Hernández-Lara, The innovation journey and crossroads of sustainability, resilience and human-centeredness: a systematic literature review, Transforming Gov. People, Process Policy (2024), https://doi.org/10.1108/TG-10-2023-0151.

[57] J. Patalas-Maliszewska, H. Łosyk, Changes in sustainable development in manufacturing in cases of unexpected occurrences—a systematic review, Sustainability 16 (2) (2024), https://doi.org/10.3390/su16020717.

[58] N. Emaminejad, L. Kath, R. Akhavian, Assessing trust in construction AI-powered collaborative robots using structural equation modeling, J. Comput. Civ. Eng. 38 (3) (2024) 04024011, https://doi.org/10.1061/JCCEE5.CPENG-5660.

[59] J.G.F. Falorca, An overview of 'intelligent' and 'smart' approaches in the context of buildings, in: J.C.G. Lanzinha, E.L. Qualharini (Eds.), Proceedings of CIRMARE 2023, Springer Nature Switzerland, Cham, 2024, pp. 589–600, https://doi.org/10.1007/978-3-031-48461-2_50.

[60] J. Dridi, M. Amayri, N. Bouguila, Unsupervised clustering-based domain adaptation for estimating occupancy and recognizing activities in smart buildings, J. Build. Eng. 85 (2024) 108741, https://doi.org/10.1016/j.jobe.2024.108741.

[61] UNESCO WHC, World heritage list [Accessed on: 08/04/2024]. http://whc.unesco.org/en/list/, 2023.

[62] M. Shan, et al., Investigating the critical issues in the conservation of heritage building: the case of China, J. Build. Eng. 51 (2022) 104319, https://doi.org/10.1016/j.jobe.2022.104319.

[63] L. Chancel, et al., World inequality Report 2022, URL. https://wir2022.wid.world/www-site/uploads/2021/12/WorldInequalityReport2022_Full_Report.pdf, 2022.

[64] C. Murphy, P.J. Carew, L. Stapleton, Towards a human-centred framework for smart digital immersion and Control for cultural heritage applications, in: IFAC-PapersOnLine, Elsevier B.V., 2022, pp. 30–35, https://doi.org/10.1016/j.ifacol.2022.12.006.

[65] S. Pansoni, et al., Artificial intelligence and cultural heritage: design and assessment of an ethical framework, in: International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, International Society for Photogrammetry and Remote Sensing, 2023, pp. 1149–1155, https://doi.org/10.5194/isprs-Archives-XLVIII-M-2-2023-1149-2023.

[66] H. Li, et al., Survey of residents of historic cities willingness to pay for a cultural heritage conservation project: the contribution of heritage awareness, Land 12 (11) (2023), https://doi.org/10.3390/land12112058.

[67] Z.M. Jones, Re-Thinking the resilience paradigm in cultural heritage, in: Lecture Notes in Networks and Systems, Springer Science and Business Media Deutschland GmbH, 2022, pp. 2526–2534, https://doi.org/10.1007/978-3-031-06825-6_241.

[68] D. Esposito, E. Cantatore, A. Sonnessa, A multi risk analysis for the planning, management and retrofit of cultural heritage in historic urban districts, in: Lecture Notes in Civil Engineering, Springer Science and Business Media, Deutschland GmbH, 2021, pp. 571–580, https://doi.org/10.1007/978-3-030-68824-0_61.

[69] F. Maietti, Digital documentation for enhancement and conservation of minor or inaccessible heritage sites, in: Contributions to Management Science, Springer Science and Business Media, Deutschland GmbH, 2022, pp. 139–156, https://doi.org/10.1007/978-3-031-14121-8_8.

[70] F.J. Rufián Fdez, et al., The documentation and protection of cultural heritage during emergencies, in: International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, International Society for Photogrammetry and Remote Sensing, 2020, pp. 287–293, https://doi.org/10.5194/isprs-archives-XLIV-M-1-2020-287-2020.

[71] Di Ludovico, D., Cities in Transformation: Smarter Reconstruction in Historic City Centres, in *Urban Book Series*. 2021, Springer Science and Business Media Deutschland GmbH. p. 493-507. 10.1007/978-3-030-77356-4_29. https://doi.org/10.1007/978-3-030-77356-4_29.

[72] X. Liang, Y. Lu, J. Martin, A review of the role of social media for the cultural heritage sustainability, Sustainability 13 (3) (2021) 1–17, https://doi.org/10.3390/su13031055.

[73] X. Liang, Participatory management for cultural heritage: social media and Chinese urban Landscape, in: Communications in Computer and Information Science, Springer, 2020, pp. 300–307, https://doi.org/10.1007/978-3-030-50732-9_40.

[74] M. Foroughi, B. de Andrade, A. Pereira Roders, Capturing public voices: the role of social media in heritage management, Habitat Int. (2023) 142, https://doi.org/10.1016/j.habitatint.2023.102934.

[75] A. Rueda Márquez de la Plata, P.A. Cruz Franco, J.A. Ramos Sánchez, Architectural survey, diagnostic, and constructive analysis strategies for monumental preservation of cultural heritage and sustainable management of tourism, Buildings 12 (8) (2022), https://doi.org/10.3390/buildings12081156.

[76] Z. Liu, M. Zhang, M. Osmani, Building information modelling (BIM) driven sustainable cultural heritage tourism, Buildings 13 (8) (2023), https://doi.org/10.3390/buildings13081925.

[77] S. Bizzarri, et al., A multidisciplinary approach to the conservation of salūt, sultanate of Oman, Stud. Conserv. 67 (S1) (2022) 23–31, https://doi.org/10.1080/00393630.2022.2084965.

[78] S. Billore, Cultural consumption and citizen engagement—strategies for built heritage conservation and sustainable development. A case study of Indore City, India, Sustainability 13 (5) (2021) 1–15, https://doi.org/10.3390/su13052878.

[79] Nared, J. and D. Bole, Participatory research on heritage- and culture-based development: A Perspective from south-east Europe, in *Urban Book Series*. 2020, Springer. p. 107-119. https://doi.org/10.1007/978-3-030-28014-7_7.

[80] S.C. Ekici, Ö. Özçakır, A.G. Bilgin Altinöz, Sustainability of historic rural settlements based on participatory conservation approach: kemer Village in Turkey, J. Cult. Herit. Manag. Sustain Dev. (2022), https://doi.org/10.1108/JCHMSD-05-2021-0087.

[81] S. Aureli, M. Del Baldo, Stakeholders' consciousness of cultural heritage and the reconciliation of different needs for sustainable development, J. Cult. Herit. Manag. Sustain Dev. 13 (4) (2023) 964–982, https://doi.org/10.1108/JCHMSD-10-2020-0156.

[82] G. Foster, R. Saleh, The circular city and adaptive reuse of cultural heritage index: measuring the investment opportunity in Europe, Resour. Conserv. Recycl. (2021) 175, https://doi.org/10.1016/j.resconrec.2021.105880.

[83] C. Ost, R. Saleh, The contribution of economics to the value chain of urban conservation, City, Culture and Society 29 (2022), https://doi.org/10.1016/

j.ccs.2022.100445.
[84] R. Redden, R.H. Crawford, Valuing the environmental performance of historic buildings, Australas. J. Environ. Manag. 28 (1) (2021) 59–71, https://doi.org/10.1080/14486563.2020.1772133.
[85] M. Bosone, F. Nocca, L. Fusco Girard, The circular city implementation: cultural heritage and digital technology, in: Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), Springer Science and Business Media, Deutschland GmbH, 2021, pp. 40–62, https://doi.org/10.1007/978-3-030-77411-0_4.
[86] N. Pintossi, D. Ikiz Kaya, A. Pereira Roders, Cultural heritage adaptive reuse in Salerno: challenges and solutions, City, Culture and Society (2023) 33, https://doi.org/10.1016/j.ccs.2023.100505.
[87] A. Vega-Bosch, et al., Cryogenics as an advanced method of cleaning cultural heritage challenges and solutions, Sustainability 14 (3) (2022), https://doi.org/10.3390/su14031052.
[88] A. Altadonna, et al., Environmental impact assessment of different manufacturing technologies oriented to architectonic recovery and conservation of cultural heritage, Sustainability 15 (18) (2023), https://doi.org/10.3390/su151813487.
[89] A.O. Shehata, et al. (3Ts) Green conservation framework: a hierarchical-based sustainability approach, Build. Environ. (2022) 224, https://doi.org/10.1016/j.buildenv.2022.109523.
[90] A. Zhou, J. Zhang, J. Zhang, Application of cultural heritage health Check in the immovable cultural heritage conservation Practice in beijing, in: ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Copernicus GmbH, 2021, pp. 215–221, https://doi.org/10.5194/isprs-annals-VIII-M-1-2021-215-2021.
[91] Y.B. Saleh, et al., The heritage city sustainability index in Malaysia, International Review for Spatial Planning and Sustainable Development 11 (4) (2023) 39–53, https://doi.org/10.14246/irspsd.11.4_39.
[92] M. Reina Ortiz, et al., Capacity building for the documentation and conservation of Latin American cultural heritage: making technology accessible and sustainable, J. Cult. Herit. Manag. Sustain Dev. 11 (2) (2021) 155–169, https://doi.org/10.1108/JCHMSD-05-2020-0076.
[93] G. Nota, G. Petraglia, Heritage buildings management: the role of situational awareness and cyber-physical systems, J. Ambient Intell. Hum. Comput. (2024), https://doi.org/10.1007/s12652-023-04750-2.
[94] X. Zhang, et al., Metaverse for cultural heritages, Electronics 11 (22) (2022), https://doi.org/10.3390/electronics11223730.
[95] P. Salonia, Role of digital technologies, robotics, and augmented realities, in: Handbook of Cultural Heritage Analysis, Springer International Publishing, 2022, pp. 1465–1496, https://doi.org/10.1007/978-3-030-60016-7_50.
[96] Q. Wang, X. Feng, X. Liu, Advances in historical wood consolidation and conservation materials, Bioresources 18 (3) (2023) 6680–6723, https://doi.org/10.15376/biores.18.3.Wang.
[97] M. Rossi, D. Bournas, Structural health monitoring and management of cultural heritage structures: a state-of-the-art review, Appl. Sci. 13 (11) (2023), https://doi.org/10.3390/app13116450.
[98] A. Vuoto, M.F. Funari, P.B. Lourenço, On the use of the digital twin concept for the structural integrity protection of architectural heritage, Infrastructure 8 (5) (2023), https://doi.org/10.3390/infrastructures8050086.
[99] X. Dang, et al., Digital twin applications on cultural world heritage sites in China: a state-of-the-art overview, J. Cult. Herit. 64 (2023) 228–243, https://doi.org/10.1016/j.culher.2023.10.005.
[100] A. Krukowski, E. Vogiatzaki, Autonomous aerial systems in service of cultural heritage protection from climate change effects, in: Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), Springer Science and Business Media, Deutschland GmbH, 2021, pp. 15–25, https://doi.org/10.1007/978-3-030-73043-7_2.
[101] C. Stanga, F. Banfi, S. Roascio, Enhancing building archaeology: drawing, UAV photogrammetry and scan-to-BIM-to-VR process of ancient roman ruins, Drones 7 (8) (2023), https://doi.org/10.3390/drones7080521.
[102] A. Marra, I. Trizio, G. Fabbrocino, Digital tools for the knowledge and safeguard of historical heritage, in: Lecture Notes in Civil Engineering, Springer Science and Business Media, Deutschland GmbH, 2021, pp. 645–662, https://doi.org/10.1007/978-3-030-74258-4_41.
[103] M. Falcone, et al., From architectural survey to continuous monitoring: graph-based data management for cultural heritage conservation with digital twins, in: International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, International Society for Photogrammetry and Remote Sensing, 2021, pp. 47–53, https://doi.org/10.5194/isprs-archives-XLIII-B4-2021-47-2021.
[104] I. Rocca, et al., Survey, diagnostics, monitoring methodology and digital twin for the conservation of the facade of the church of santa maria di nazareth in venice, in: International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, International Society for Photogrammetry and Remote Sensing, 2023, pp. 1331–1336, https://doi.org/10.5194/isprs-Archives-XLVIII-M-2-2023-1331-2023.
[105] S. Monchetti, et al., The research project "CHARMING PISTOIA": an integrated HBIM project for preservation and maintenance of heritage structures, in: Procedia Structural Integrity, Elsevier B.V., 2022, pp. 1988–1995, https://doi.org/10.1016/j.prostr.2023.01.254.
[106] S. Bruno, et al., Verbum - virtual enhanced reality for building modelling (virtual technical tour in digital twins for building conservation), J. Inf. Technol. Construct. 27 (2022) 20–47, https://doi.org/10.36680/j.itcon.2022.002.
[107] F.M. La Russa, C. Santagati, Historical sentient – building information model: a digital twin for the management of museum collections in historical architectures, in: International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, International Society for Photogrammetry and Remote Sensing, 2020, pp. 755–762, https://doi.org/10.5194/isprs-archives-XLIII-B4-2020-755-2020.
[108] A. Ippolito, et al., Digital documentation strategies for the knowledge of the basilica of santa maria in Trastevere, in: International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, International Society for Photogrammetry and Remote Sensing, 2023, pp. 735–742, https://doi.org/10.5194/isprs-Archives-XLVIII-M-2-2023-735-2023.
[109] T.A. Nguyen, et al., Integration of H-bim, virtual reality, and augmented reality in digital twin era - a case study in cultural heritage, in: Lecture Notes in Civil Engineering, Springer Science and Business Media, Deutschland GmbH, 2023, pp. 303–312, https://doi.org/10.1007/978-981-19-3303-5_24.
[110] A. Darwish, A.E. Hassanien, IoHCT: internet of cultural heritage things digital twins for conservation and health monitoring of cultural in the age of digital transformation, in: Studies in Systems, Decision and Control, Springer Science and Business Media, Deutschland GmbH, 2022, pp. 1–21, https://doi.org/10.1007/978-3-030-96802-1_1.
[111] J. Borucka, S. Parrinello, VREA Project - a digital curator for architecture and digital perspectives for heritage management and enhancement, in: International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, International Society for Photogrammetry and Remote Sensing, 2023, pp. 289–296, https://doi.org/10.5194/isprs-Archives-XLVIII-M-2-2023-289-2023.
[112] N. Haddad, 3D and 2D visual digital technologies and cultural heritage documentation for conservation and monitoring: a critical review and assessment, in: Optoelectronic Devices in Robotic Systems, Springer International Publishing, 2022, pp. 257–288, https://doi.org/10.1007/978-3-031-09791-1_10.
[113] F. Chen, et al., Deformation monitoring and thematic mapping of the Badaling Great Wall using very high-resolution interferometric synthetic aperture radar data, Int. J. Appl. Earth Obs. Geoinf. (2021) 105, https://doi.org/10.1016/j.jag.2021.102630.
[114] P. Gawronek, T. Noszczyk, Does more mean better? Remote-sensing data for monitoring sustainable redevelopment of a historical granary in Mydlniki, Kraków, Heritage Science 11 (1) (2023), https://doi.org/10.1186/s40494-023-00864-0.
[115] A. Lerario, The IoT as a key in the sensitive balance between development needs and sustainable conservation of cultural resources in Italian heritage cities, Sustainability 12 (17) (2020), https://doi.org/10.3390/su12176952.
[116] D. Longo, et al., Cultural Heritage and Interoperable Open Platforms: Strategies for Knowledge, Accessibility, Enhancement and Networking, vol. 241, WIT Transactions on Ecology and the Environment, 2020, pp. 371–382, https://doi.org/10.2495/SDP200301.
[117] E. Piaia, et al., BIM-Based cultural heritage asset management tool. Innovative solution to orient the preservation and valorization of historic buildings, Int. J. Architect. Herit. 15 (6) (2021) 897–920, https://doi.org/10.1080/15583058.2020.1734686.
[118] G.A. Giacobone, G. Mincolelli, S. Imbesi, Inclusive Cultural Heritage in Europe: Co-designing an Accessible User Experience for Digital Architectural Conservation, Journal of Architectural Conservation, 2023, https://doi.org/10.1080/13556207.2023.2296216.
[119] A. Boeri, et al., The 4CH project and enabling technologies for safeguarding the Cultural Heritage, Techne 25 (2023) 162–172, https://doi.org/10.36253/

techne-13711.

[120] B. Turillazzi, et al., Heritage-led Ontologies: Digital Platform for Supporting the Regeneration of Cultural and Historical Sites, vol. 249, WIT Transactions on Ecology and the Environment, 2020, pp. 307–318, https://doi.org/10.2495/SC200261.

[121] A. Boeri, et al., Temporary transformations to access and experience sustainable city public spaces, WIT Trans. Ecol. Environ. 249 (2020) 43–55, https://doi.org/10.2495/SC200051.

[122] F. Spettu, et al., Web platforms for cultural heritage management: The parco archeologico del colosseo case study, in: International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, International Society for Photogrammetry and Remote Sensing, 2023 https://doi.org/10.5194/isprs-archives-XLVIII-M-2-2023-1493-2023, 1493-1500.

[123] M. Moreno, et al., ART-RISK 3.0 a fuzzy—based platform that combine GIS and expert assessments for conservation strategies in cultural heritage, J. Cult. Herit. 55 (2022) 263–276, https://doi.org/10.1016/j.culher.2022.03.012.

[124] L. Mateus, et al., Proposal for an information system for the Portuguese historical and military heritage based on a sustainable, innovative and inclusive management model, in: Lecture Notes in Networks and Systems, Springer Science and Business Media Deutschland GmbH, 2024, pp. 313–322, https://doi.org/10.1007/978-3-031-44131-8_31.

[125] K.M. Doan, N.P. Bui, T.M. Doan, Towards developing the smart cultural heritage management of the French colonial villas in Hanoi, Vietnam, International Journal of Sustainable Construction Engineering and Technology 12 (1) (2021) 296–313, https://doi.org/10.30880/ijscet.2021.12.01.028.

[126] T.K. Gireesh Kumar, Preserving the distributed fragments of cultural heritage: need for building a sustainable information system in India, Preservation, Digital Technology and Culture 51 (2) (2022) 51–61, https://doi.org/10.1515/pdtc-2021-0029.

[127] M.G. Masciotta, et al., A digital-based integrated methodology for the preventive conservation of cultural heritage: the experience of HeritageCare project, Int. J. Architect. Herit. 15 (6) (2021) 844–863, https://doi.org/10.1080/15583058.2019.1668985.

[128] J. Korro Bañuelos, et al., The role of information management for the sustainable conservation of cultural heritage, Sustainability 13 (8) (2021), https://doi.org/10.3390/su13084325.

[129] Y. Li, et al., A review of the tools and techniques used in the digital preservation of architectural heritage within disaster cycles, Heritage Science 11 (1) (2023), https://doi.org/10.1186/s40494-023-01035-x.

[130] M.S. Tzima, et al., An application of machine learning algorithms by synergetic use of SAR and optical data for monitoring historic clusters in Cypriot cities, Energies 16 (8) (2023), https://doi.org/10.3390/en16083461.

[131] E. Alexakis, et al., A novel application of deep learning approach over IRT images for the automated detection of rising damp on historical masonries, Case Stud. Constr. Mater. 20 (2024), https://doi.org/10.1016/j.cscm.2024.e02889.

[132] F. Rodrigues, et al., Application of deep learning approach for the classification of buildings' degradation state in a BIM methodology, Appl. Sci. 12 (15) (2022), https://doi.org/10.3390/app12157403.

[133] S. Masini, et al., Revealing the structural behaviour of Brunelleschi's Dome with machine learning techniques, Data Min. Knowl. Discov. (2024), https://doi.org/10.1007/s10618-024-01004-3.

[134] V. Croce, et al., H-BIM and artificial intelligence: classification of architectural heritage for semi-automatic scan-to-BIM reconstruction, Sensors 23 (5) (2023), https://doi.org/10.3390/s23052497.

[135] F. Matrone, M. Martini, Transfer learning and performance enhancement techniques for deep semantic segmentation of built heritage point clouds, Virtual Archaeology Review 12 (25) (2021) 73–84, https://doi.org/10.4995/var.2021.15318.

[136] C. Piselli, et al., An integrated HBIM simulation approach for energy retrofit of historical buildings implemented in a case study of a medieval fortress in Italy, Energies 13 (10) (2020), https://doi.org/10.3390/en13102601.

[137] J. Moyano, et al., Integration of dynamic information on energy parameters in hbim models, in: International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, International Society for Photogrammetry and Remote Sensing, 2023, pp. 1089–1096, https://doi.org/10.5194/isprs-Archives-XLVIII-M-2-2023-1089-2023.

[138] A. Massafra, G. Predari, R. Gulli, Towards digital twin driven cultural heritage management: a HBIM-based workflow for energy improvement of modern buildings, in: International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, International Society for Photogrammetry and Remote Sensing, 2022, pp. 149–157, https://doi.org/10.5194/isprs-archives-XLVI-5-W1-2022-149-2022.

[139] E. Lucchi, Integration between photovoltaic systems and cultural heritage: a socio-technical comparison of international policies, design criteria, applications, and innovation developments, Energy Pol. (2022) 171, https://doi.org/10.1016/j.enpol.2022.113303.

[140] ICLEI. *Adaptive Reuse of Cultural Heritage*. 2020 URL: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwjgi-7i67SFAxU4hf0HHZDYCagQFnoECCQQAQ&url=https%3A%2F%2Ficlei-europe.org%2Ffileadmin%2Ftemplates%2Ficlei-europe%2Flib%2Fresources%2Ftools%2Fpush_resource_file.php%3Fuid%3DslMYA476&usg=AOvVaw3PHh32moYSXElfAIMJFlHw&opi=89978449.

[141] United Nations, Sendai framework for disaster risk reduction 2015 - 2030, URL: https://www.preventionweb.net/files/43291_sendaiframeworkfordrren.pdf, 2015.

[142] UNESCO, Recommendation on the historic urban Landscape, URL: https://unesdoc.unesco.org/ark:/48223/pf0000215084.page=55, 2011.

[143] ICCOMOS, International cultural tourism charter, URL: https://www.icomos.org/images/DOCUMENTS/Charters/INTERNATIONAL_CULTURAL_TOURISM_CHARTER.pdf, 1999.

[144] European Commission, A Renovation Wave for Europe - Greening Our Buildings, Creating Jobs, improving lives, 2020 URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0662.

[145] European Commission, New European Bauhaus Academy to build skills for sustainable construction with innovative materials, URL: https://ec.europa.eu/commission/presscorner/api/files/document/print/en/ip_23_6593/IP_23_6593_EN.pdf, 2024.

[146] A. Ajoudani, et al., Progress and prospects of the human–robot collaboration, Aut. Robots 42 (5) (2018) 957–975, https://doi.org/10.1007/s10514-017-9677-2.

[147] A. Holzinger, Interactive machine learning for health informatics: when do we need the human-in-the-loop? Brain Informatics 3 (2) (2016) 119–131, https://doi.org/10.1007/s40708-016-0042-6.

[148] J. Zhang, et al., Human-in-the-loop optimization of exoskeleton assistance during walking, Science 356 (6344) (2017) 1280–1284, https://doi.org/10.1126/science.aal5054.

[149] F. Longo, A. Padovano, S. Umbrello, Value-oriented and ethical technology engineering in industry 5.0: a human-centric perspective for the design of the factory of the future, Appl. Sci. 10 (12) (2020), https://doi.org/10.3390/app10124182.

[150] J.J. Martín-del-Rio, et al., Analysis of the materials and state of conservation of the medieval rammed earth walls of Seville (Spain), J. Build. Eng. 44 (2021) 103381, https://doi.org/10.1016/j.jobe.2021.103381.

[151] J.L. Parracha, et al., Vernacular earthen buildings from Leiria, Portugal – architectural survey towards their conservation and retrofitting, J. Build. Eng. 35 (2021) 102115, https://doi.org/10.1016/j.jobe.2020.102115.

[152] A. Jiménez Rios, Learning from the Past: parametrical analysis of cob walls, Appl. Sci. 13 (15) (2023) 9045, https://doi.org/10.3390/app13159045.

[153] B. Schleich, et al., Shaping the digital twin for design and production engineering, CIRP Ann. - Manuf. Technol. 66 (1) (2017) 141–144, https://doi.org/10.1016/j.cirp.2017.04.040.

[154] Y. Sewasew, S. Tesfamariam, Historic building information modeling using image: example of port city Massawa, Eritrea, J. Build. Eng. 78 (2023) 107662, https://doi.org/10.1016/j.jobe.2023.107662.

[155] A. Jiménez Rios, V. Plevris, M. Nogal, Uncertainties in the synthetic data generation for the creation of bridge digital twins, in: 5th International Conference on Uncertainty Quantification in Computational Science and Engineering (UNCECOMP), 2023 https://doi.org/10.7712/120223.10323.20020, Athens, Greece.

[156] A. Jiménez Rios, V. Plevris, M. Nogal, Synthetic data generation for the creation of bridge digital twins what-if scenarios, in: 9th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN), 2023 https://doi.org/10.7712/120123.10760.21262, Athens, Greece.

[157] S.M. Sajjadian, Data in construction; from drawings to smart operations, J. Build. Eng. (2024) 110094, https://doi.org/10.1016/j.jobe.2024.110094.

[158] C. Shorten, T.M. Khoshgoftaar, A survey on image data augmentation for deep learning, Journal of Big Data 6 (1) (2019) 60, https://doi.org/10.1186/s40537-019-0197-0.

[159] J. Moyano, et al., Semantic interoperability for cultural heritage conservation: workflow from ontologies to a tool for managing and sharing data, J. Build. Eng. 80 (2023) 107965, https://doi.org/10.1016/j.jobe.2023.107965.

[160] S. Syahrizal, F. Yasmi, M. Thomson, AI-enhanced teaching materials for education: a shift towards digitalization, International Journal of Religion 5 (1) (2024) 203–217, https://doi.org/10.61707/j6sa1w36.

[161] F. Amin, et al., Diabetes and its associated factors: a Retrospective cohort analysis of a large database at Indus Hospital Health Network, Pakistan J. Med. Sci. 40 (2) (2023) https://doi.org/10.12669/pjms.40.2(ICON).8948, ICON.

[162] V. Plevris, G. Papazafeiropoulos, A. Jiménez Rios, Chatbots put to the test in math and logic problems: a comparison and assessment of ChatGPT-3.5, ChatGPT-4, and Google Bard AI 4 (4) (2023) 949–969, https://doi.org/10.3390/ai4040048.

[163] United Nations, Climate Action Net Zero, 2024. https://www.un.org/en/climatechange/net-zero-coalition. (Accessed 23 April 2024).

[164] United Nations, Climate action acceleration Agenda, URL: https://www.un.org/sites/un2.un.org/files/un_sgs_acceleration_agenda.pdf, 2023.