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Review

Review of preventive conservation in museum buildings

Elena Lucchi*

Politecnico di Milano, 9, via Bonardi, 20133 Milano, Italy

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ABSTRACT

The paper presents a critical review of preventive conservation in museum buildings. It summarizes theories and approaches spanning from fifty years (1965–2016) in Europe, Canada, and US. From a wide range of bibliography (110 publications composed by books, guidelines, researches, and other documents), the study wants to identify recurring topics in different historical periods, geographical countries, and cultural approaches. Main fields of action of preventive conservation regard: damage preservation and environmental management; architecture and exhibit design; environmental and energy simulations; monitoring, recording and controlling of the environmental agents; management and training. Particularly, the consciousness of the importance of the environmental impact on museum buildings, introduced a broad debate on the definition of the standards for minimizing and assessing heritage risks, considering single factors (light, temperature, relative humidity, and indoor air pollution) and their cumulative effects. The attention on energy efficiency started from the last decade, focusing mainly on energy audit, modelling, and retrofit of historic buildings. Generally, these works are not specific for museums but, anyway, criteria, methodologies, monitoring procedures, simulation models, and technical solutions are suitable also for museum buildings. The design has central role both for passive and active indoor control. Besides, everyday management, regular maintenance, and training are considered key actions for promoting safeguard, users' comfort and energy efficiency. The research aims to serve as a reference for technicians and conservators to amplify and to ordinate their knowledge in the field of preventive conservation in museum buildings.

1. Introduction

"[...] Conservation today is a complex activity. Just a few years ago it was much simpler, and some decades before that, it did not even exist" ([1], p. 1). Today, the conservation activities play an important role for transmitting the "meaning" of cultural heritage. They influence the appearance, the materials, and the structures of cultural items [2]. The International Council of Museums (ICOM), authoritative on matters of cultural heritage and museum buildings, defines the conservation as: "[...] all measures and actions aimed at safeguarding tangible cultural heritage while ensuring its accessibility to present and future generations" [3]. Particularly, three forms of conservation are introduced: "[...] conservation embraces preventive conservation, remedial conservation and restoration" [3]. These activities are target to "future", "current" and "past" deteriorations:

- "preventive conservation" aims at avoiding and minimizing "future" losses;
- "remedial conservation" aims at arresting "current" damage or reinforcing the structure while;
- "restoration" aims at refurbishing "past" alterations. In all case, conservation is no longer an action for conserving truths, but is a decision on the meanings of cultural assets [1].

Referred to the "future", preventive conservation is essential to minimize decay, enhance cultural features, and valorize economic values of the heritage. Historically, it is mainly applied to museum buildings, the places dedicated to preservation, enhancement and transmission of cultural values. In the last century, the need of the integration between the conflicting requirements of safeguard and tourism promotion has developed an international notion of "museum", considered as a dynamic place with different roles [4]. Beside the traditional functions of research, preservation, display, management, and storage, new activities and spaces arose, related to marketing, communication, education, and tourist entertainment (e.g. conference rooms, laboratories, bookshops, libraries, play zones, restaurants, cafeterias, and shops) [5]. This situation complicated a lot the environmental conservation of the heritage.

* Correspondence. EURAC Research, 1, viale Druso, 39100, Bolzano, Italy.
E-mail address: elena.lucchi@polimi.it

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Preventive conservation includes any strategies, actions, skills, and judgments to balance heritage protection and public access [3,6]. Its plan for a museum building involves a variety of topics, in order to assure damage minimization, free access, users' comfort, energy efficiency, public enjoyment, communication, education, and safety precaution. It requires the achievement of the right equilibrium between a number of complex and frequently contradictory environmental parameters. Damage causes the progressive loss of tangible and intangible artifacts, related to physical properties, significance, economic value, and social-educative role [3]. Thus, care of building and collection needs a strict control of light, air temperature, relative humidity, and pollutants for minimizing losses and ensuring long-term control of indoor conditions. This situation often imposes the use of lighting and air-conditioning systems, with consequently high-energy consumptions [2,5,7–11]. Vice-versa, free access, tourist visitation, and cultural learning require appropriate comfort levels for the occupancies [12–16]. However, it has been experienced that the over-visitation of the monuments may catalyze the deterioration, due to variable environmental conditions, improper handling, air and indoor pollution, impact of HVAC, and so on [16]. Furthermore complex activities (i.e. restoration, didactics, selling, cleaning, and maintenance), laboratories (tanning, taxidermy, and embalming), food areas, and gardens may generate microclimatic instability and pollutants [5,12,13,17,18], not always compatible with users' comfort. Finally, the museums have an important educational role for citizens and visitors related to environmental sustainability and energy efficiency [7,13]. Therefore, preventive conservation is the best sustainable and cost-effective strategy to reduce energy demands and operative costs, without jeopardizing conservation and human comfort.

2. Aims and methodology

The paper presents a review of preventive conservation in museum buildings. Given the complexity and the extension of the topic treated, we are aware that a complete and exhaustive presentation of all topic is not possible. The paper tried to define a historiography of preventive conservation, departing from de Guichen's [19], Lambert's [20,21] and Muñoz Viñaz's [1] theories. After introducing the early history of preventive conservation, the research summarizes finding spanning from 1965 to 2016, trying to outline a critical historiography through pioneering studies and strategic theories with different approaches. Fifty years of its history are summarized, simplifying the technical aspects and considering a great variety of bibliography (more than 110 publications and 40 Internet sites in English, Italian, and French). It contains a wide range of publications, composed by books, guidelines, conference and scientific papers, standards, legislations, and other materials elaborated by European researches, museum institutions, and associations. The selected literature is written mainly in English, Italian, and French, due to the accessibility of the papers and the understanding of the languages. Furthermore, many Swedish, Danish, and Dutch studies on this topic has been translated in English. In addition, English is the language commonly used in scientific papers, both for journals and conference papers. We looked also for Spanish texts, but we do not find interesting texts accessible by the Internet sites. We looked for publications on this topic in Asia, discovering a very different approach oriented mainly to restoration, renovation, and reconstruction instead of conservation. Thus, we decided not to consider these publications. Clearly, taking into consideration German, Swedish and Danish languages, the selected bibliography would be wider. Also, the accessibility to museum publications and old books conserved in local libraries can further develop this research. This situation may exclude relevant contributions at national level not translated in English. In addition, it may omit the field not used to publish in English (i.e. humanities, social and legal fields). Thus, we hope that the research will be expanded considering other studies, especially from the countries that worked extensively on this subject (i.e. Germany, France, Netherlands and Sweden). Aware of these limits, the study wants to identify recurring topics in different historical periods, geographical countries (mainly Europe, Canada, and US), cultural approaches, and so on. The research neither means to be exhaustive or definitive, but simply aims to serve as a reference for technicians and conservators to amplify and to ordinate their knowledge in the field of preventive conservation in museum buildings.

3. Overview on preventive conservation theories

The early literature on conservation of cultural heritage was characterized by the progressive integration of science into conservation activities, providing instructions to avoid moisture, insects, and pest problems through a careful planning of the indoor environment [2,15,20,21]. Lambert [21] described a cohesive body of knowledge emerged in England during the XVI Century known as "housekeeping". It consisted in practical advices for the maintenance and the staff management, to control the indoor climate in estate homes. The parameters considered were light, heat, humidity, insects, dust, and damage. Thus, the first literature encourage maintenance, continuous care, and management as important action for preventing the damage of heritage. Lambert [21] found also several examples from the XVII Century that reveal a preoccupation for the protection of cultural heritage from further damage or restoration treatments. Muñoz Viñaz [1] revisited the tenets of the classical theories ranging from XVIII to XX centuries, augmenting concisely the early history of the contemporary theory of conservation. He introduced the set of norms defined by Pietro Evans in the XVII Century (1777) for preventing the excess committed by the restores in the Venetian paintings (i.e. use non corrosive products, no cover the lacunas in old paintings, . . .). Today, these advices were an important point for setting out the criteria of minimum intervention and physical compatibility between heritage and restoration activities. The fundamental debate on conservation Eugène Viollet-le-Duc and John Ruskin signed two different visions of restoration and preservation. First, Viollet-le-Duc authorized to "fill-in-the blanks" ([1], p. 4) for not completed monuments and buildings. On the contrary, Ruskin criticized the work made for rebuilt damaged buildings [1]. He disapproved the restoration process for destroying the authenticity of heritage buildings and disturbing the original remnants. He and his "anti-restoration movement" fought the continuous maintenance as fundamental for limit damage and restoration activities: "[. . .] take proper care of your monuments and you will not need to restore them" ([22] p. 196). Other theories tried to balance between the extremes proposed by Ruskin and Viollet-le-Duc (i.e. Camillo Boito, Beltrami, and Gustavo Giovannoni), but "[. . .] no single theory managed to clearly triumph over the others" ([1], p. 5). These theories created considerable divergences between "conservation" and "restoration" activities. For this reason, several institutions focused their activity on the normalization of the restoration principles, promulgating "Charters" and normative documents. The publication tried to compare the work of scientists and technicians. The first document was the Athens Charter [23] published in 1931, which was followed by several contributions [24–26]. Particularly, the Athens [23] and the Venice [24] Charters influenced the thinking on cultural heritage in many countries, providing the basis for a new approach based on the conservation principles.

After these less sporadic cases, the idea of "cultural heritage protection" changed significantly in the last century [20,21,23,26–28].

During the experiences of the two World Wars, many objects were damaged for the high humidity conditions during their storage [29]. Consequently, to face urgent or catastrophic events and to justify increasing expenditure for protecting entire collections during the Wars, several countries planned to implement their conservation activities [21]. In these years, a number of scientific laboratories were created into international museums (i.e. National Gallery, British Museum, Berlin Königlichen Museen, Musée du Louvre, Musée de Belgique, Fogg Art Museum at Harvard University) to study the influence of the environment on heritage decay [10]. Furthermore, the first devices for active climate control (i.e. central heating, artificial lighting and facilities) were installed into European and American museums, to set appropriate indoor conditions and to solve the typical disadvantages of old buildings [10,30].

The traditional logic of "restoration" intended as a "[. . .] moment of therapeutic and ex-post conservation" [31] was gradually abandoned [32]. Thanks to the collaboration between conservators and scientists (1930–1950), a new vision of "prevention" arose as "[. . .] regular and permanent maintenance" [23] or "[. . .] modest maintenance actions repeated over time" [25]. In practice, the ideas of "ex-ante prevention" or "systematic care" [145] replaced the traditional logics of "remedial conservation" or "restoration" for solving urgent problems already occurred [3].

Plenderlith [29] made a systematic exploration of the deterioration mechanisms, demonstrating the possibilities to minimize the physical harms on antiquities and artworks mainly recognizing the causes of damage. His conservation guidance took into consideration: storage conditions, temperature, relative humidity, light, dust, biological attacks, and damage caused by the public [29]. These studies had a remarkable development in the Sixties, in response to the emergencies caused by floods and other catastrophic events in several European museums and city centers [2,20,33,34].

A new field in the conservation discipline emerged from these studies in early 1970s, focusing mainly in the museum sector due to the specific problems related to the collection [13,21,34,35,146]. There are various definitions of "preventive conservation":

- "[. . .] non-interventive actions taken to prevent damage and minimize deterioration of a museum object" ([6] p. 3.20);
- "[. . .] provision of suitable environmental protection against the known of natural or artificial causes of deterioration of museum specimens and works of art" ([4] p. 45);
- "[. . .] all measures and actions aimed at avoiding and minimizing future deterioration or loss [. . .] These measures and actions are indirect–they do not interfere with the materials and structures of the items. They do not modify their appearance" ([3] p. 37);
- "[. . .] the full range of actions designed to safeguard or to increase the life expectancy of a collection or an object" ([36], p. 30).

Also, Muñoz Viñaz defined preservation as "[. . .] non-deliberate action of perceptible changes to heritage items" ([1], pp. 15), while restoration deals with the deliberate action of perceptible changes to them. Preservation is divided into:

- "direct preservation" that refers to changes in the object and time-limited actions; and
- "environmental preservation" that refers to changes in the environment of the objects and thus to preventive conservation. Final, de Guichen proposed a historiography of the preventive conservation. He divided the path of preventive conservation into different phases: "[. . .] the first one from 1965 to 1975, when awareness on the question arose; then from 1976 to 1985, when the term properly got into the debate; after that, from 1986 to 1995, the strategy was designed" [19].

The early history of preventive conservation is strictly connected with the origin of the national laws for cultural heritage protection. In Europe, the "European Cultural Convention" (1954) developed a mutual understanding and a reciprocal appreciation of their cultural diversity, to safeguard, to study and to promote European policies for the conservation and enhancement of its heritage. The US legislation on heritage protection concerned principally with historical sites and monuments, rather than art works or international treasures [37]. The early laws considered the antiquities (1906), the historic sites and buildings (1935), the archaeological resources (1960), and more generally the historical preservation (1949; 1966).

3.1. 1965–1975: pioneer theories

The growing interest on the "museum climatology" [38] was testified from the first conference explicitly dedicated to this topic, organized in 1967 by the Institute for Conservation of Historic and Artistic Works (IIC) [39]. The workshop presented many practices to minimize physical harms on heritage, studying the influence of the environmental parameters (temperature, relative humidity, light, and biological attacks) [20].

The international debate on this topic introduced the items of "preventive restoration" [27] and "planned conservation" [31] to secure a suitable physical environment for the objects. Related to the national laws for cultural heritage protection, the pioneer theories focused on buildings and heritage sites. The Brandi's theory of "preventive restoration" [27] was based on the respect for the heritage, recognizing its physical and aesthetic values. For this reason, it changed the traditional idea of restoration, including the maintenance procedures for limiting degradation and avoiding or postponing any restoration. On this basis, Urbani [31] introduced the notion of "planned conservation" as «[. . .] periodic measures taken to maintain and to reduce the rate of deterioration of ancient materials as much as possible» ([31], tr. en.). He settled concrete actions and measurable results to be applied into large urban areas (i.e. the "Pilot plan for the programmed conservation of cultural heritage in Umbria") [143]. The hazards considered for defining heritage vulnerability and deterioration factors are [40]: geological, seismic and meteorological risks, pollution, and depopulation. Urbani's theory was broadly criticized due to the link with the private sector. Therefore, it wasn't integrated into government policies. Also the concrete actions expected weren't realized. Italy's failure was instructive for other countries "[. . .] to raise public awareness for the importance of long-term planning for cultural heritage protection and to allocate resources effectively" [21]. These theories underlined the fundamental activities for the conservation of the cultural heritage, such as research, preservation, management and maintenance. The same actions were adopted in the following decades for the environmental protection of pieces of arts, treasures, and so on. Furthermore, they showed the importance of: the long-term planning for organizing resources, activities and funding for protecting the heritage, and the support of the national policies.

In the same years, the American laws on heritage protection concerned mainly building sites and structures [37]. Particularly, the "National Historic Preservation Act" (1966) introduced the importance of the maintenance activities for conserving districts, sites, buildings, properties, and objects. Additionally, the "National Environmental Policy Act" (1969) focuses on the economic and technological values of the heritage, not only on its environmental and cultural values. The interrelationship between the two acts developed a growing attention on the preservation of historic and cultural aspects of the national heritage [37]. Likewise, the international heritage laws made by the UNESCO (1970; 1972) introduced three typology of cultural heritage [41]:

- monuments;
- groups of buildings;
- sites.

In all cases, they suggested to integrate the protection of that heritage into comprehensive planning programs (i.e. inventories, export certificates, monitoring trade, educational campaigns, and so on), to safeguard better the patrimony and to support the international cooperation (i.e. import and export controls, legal issues relate to acquisition, administrative controls) [41].

3.2. 1976–1985: debate on preventive conservation

The consciousness of the importance of the "environmental impact" on heritage introduced a broad discussion on museum climate and "environmental management". The second era of preventive conservation (1976–1986) started with this debate on standard conditions for preserving the heritage [19]. International organizations such as the ICOM (founded in 1946) [42] and the International Centre for the Study of Preservation and Restoration of Cultural Property (founded as Rome Center in 1956 and transformed in ICCROM since 1977) [43] played a crucial role for establishing standards for setting out the optimal environmental conditions for safeguarding the cultural heritage. The attention moved from the immovable (i.e. buildings and sites) to the movable heritage (i.e. pieces of art, sculptures, treasures, books, documents, and so on). The fundamental aspects treated were light and hygrothermal levels to reduce damage on pieces of art [44,45].

Few years later, Thomson [38], the coordinator of the IIC conference [39], founded the basis of the "preventive medicine of conservation" in a systematic way, organizing standards, rules, and experimentations. He defined the "[. . .] essence of preventive conservation, which begins by asking «why» we conserve instead of «what»" ([8], p. 4). Although the book included specific environmental standards for painting collections into London's museums, it provided enough information for interpreting and selecting the values for others climates, buildings, or budgets. He introduced two "conservation classes": "Class 1" or "20/50 standard" appropriated "[. . .] for major National museums, old or new, and also for all important new museum buildings" ([38], p. 268); and "Class 2" without any air-conditioning or automatic light control "[. . .] to avoid the major dangers while keeping cost and alteration to a minimum" ([38], p. 268). These recommendations were taken up as a point of reference for many museums and international standardization committees all over the word, probably because they are based on common practices and widespread literature. Their diffusion in museums was very wide. Thomson's recommendations were criticized harshly for the poor scientific evidence [46,47]. Particularly, Brown and Rose [47] noted that "Class 2" was considered as synonymous of second class, so the conservators preferred to ensure the "first class environment". In addition, the control of the "20/50 standard" was easy to obtain, also without specific skills and expertise. As consequence, the literature underlined the growth of damage linked to these thresholds [46,47]. On the other hand, this study revealed the central role of the environmental control for reducing damage, losses, or even destruction of the exhibits [35,48,49].

In the meantime, de Guichen [8] defined a comprehensive plan for preventive conservation based on the implementation of direct and indirect measures to reduce natural and human causes of deterioration. He considered not only the environmental levels, but also teaching and dissemination activities (e.g. he organized the travelling exhibition "Conservation in Museum" in 1978 and the ICCROM's course on "Museum climate" in 1980). He developed the consciousness that the application of the optimal environmental levels for heritage conservation requires the involvement of the museum staff.

Furthermore, the Canadian Conservation Institute (CCI) created the "Framework for Preventive Conservation", and the Light Damage Calculator (1980s) [50], spreading these themes also in America. In US few years later, the Bay Foundation funded the "Pilot Program in Collections Care" (1986), the National Park Service (NPS, 1990) and the Getty Conservation Institute (GCI, 1990–1995) began offering training on this topic [51–53]. The NPS and the GCI published also very specific book on damage, conservation and management criteria (i.e. damage due to airborne particle, corrosion, and so on). Finally, the importance of the preventive conservation was sanctioned by two international conferences entirely dedicated to this theme held by the Association des restaurateurs d'art et d'archéologie de formation universitaire (ARAAFU) in Paris (1992) and IIC in Ottawa (1994) [54,55].

3.3. 1986–1995: strategic design

The third era of preventive conservation [19] (1986–1995) started defining strategies, guidelines and courses. Initially, following the Thomson's approach, the environmental parameters are considered in a separate way, defining "safe" levels and allowable ranges for light [56–60], climate [13,61,62], and concentration of pollutants [12,63]. Later, Camuffo [35] demonstrated the cumulative effects of the interactions among these parameters. After several experimental monitoring on cultural heritage, he underlined the concept of "historical climate" that considers past climatic conditions as a priority for safeguarding the cultural identity for the future. Camuffo's work outlined Italian [64–66] and European [67–69] standards on preventive conservation of museum collections, considering also human comfort. Particularly, in Italy specific standards suggested the correct microclimatic parameters for protecting graphic documents [66] and artifacts with historical and artistic interest [64]. They gave, also, some recommendations about monitoring, processing, and summarizing procedures [65,70]. Following this approach, the Italian "Ministero per i Beni e le Attività Culturali e il Turismo" (MiBACT) [144] produced a legislation that defines specific requirements and qualification schemes for museum qualification [71]. The European standards developed a different point of view on the environmental control, defining procedures and methods rather than strictly requirements [67–69,72,73]. Particularly, EN 15757 standard [67] determined the target ranges and variability of microclimate conditions (temperature and relative humidity) developing the idea of the "historical climate" announced by the Camuffo's theory [35] and the UNI 10969 standard [65].

In parallel, several cultural institutions drafted guidelines and policies for environmental and risks managements. The environmental management applied to museum buildings started from practical experiences and adapted the standards to the complexity and the variety of the museum heritage [11,74–77]. The actions ranged from building maintenance, control of staff practices, climate control, and legislation. Similarly, the Granada (1985) and the Malta (1992) conventions underlined the need for statutory measures for heritage protection, including repair, reuse, control of buildings and otherwise intervention for preventing the damage. Several years later, the ICCROM [48] proposed a method for supporting the conservative management in museums at international level.

3.4. 1996–2005: researches and operative tools

Connected to these studies, several works analyzed the contribution of the original architectural features and the construction materials for the passive control of the climate [78–80]. Two European (EU) researches financed into the JOULE III (1995–1999) and SAVE II (1996–2000) Programs generated proposal for the passive design of archeological museums in the Mediterranean countries [79,80]. Other researches (mainly developed in US or for international associations) considered the potential of the traditional architecture for reaching the environmental standards in developing countries with limited funding [70,78].

In these decades, the works focused on the development of case studies, tools and activities for controlling and preventing the damage. "Preventive Conservation" as a key action for the research was included in the V Framework Program (FP) of the European Community (1999). Even since, there was a gap between the museum works and the implementation of research results. First, the project "Global Climate Change Impact on Built Heritage and Cultural Landscapes" (Noah's Ark) (2002–2006) focused on the impact of global climate change on European built heritage exposed to outdoor conditions. The risks on buildings (especially on façades) were due to the increasing of precipitation and traffic pollutants. Others projects developed specific tools and technology solutions. As an example, the project "Innovative Modelling of Museum Pollution and Conservation Thresholds" (IMPACT) settled web-based tools and passive absorbers to help museums deal with pollution problems (2000–2004). Furthermore, the research "Preventive Conservation Strategies for Organic Objects in Museums, Historic Buildings and Archives" (MASTER) produced a specific sensor for evaluating the decay of organic objects (2003–2006).

In parallel, in this period many European countries founded new acts for museum with the definition of the organizational structures at national level, the qualitative standards, and the criteria obtain state funding (i.e. Estonia 1996; Hungary 1997; UK, 2001; Italy, 2001: Greece and France 2002, Portugal, 2004; Ukraine, 2006; Poland, 2007). Also in absence of specific museum acts, the museum policies were actively developed through a series of white papers defining organizational structures, general scope and specific aims (i.e. Norway, 2002; Belgium, 2006; Macedonia and Moldova, 2007; Serbia, 2007).

Another important topic that emerged in these years is the risk-based assessment, based on the practical experience in the museum management [142]. The GCI first developed an assessment strategy for American museums, in collaboration with the National Institute for Conservation (NIC) [12,81]. They focused on both the physical and the organizational aspects of the museum environment, considering the complex interrelationship among:

- collections sensitivities;
- building performance;
- risks from the environment and use;
- risks from policies and practices relating to management, operations, or visitation [81].

Based on these experiences, other museums published basic conservation manuals with risk assessment surveys and checklists for evaluating the collection's condition. Waller propose a complex risk model based on the comparison among all the factors that affect the heritage [82]. Knell [15] suggested four scientific research levels for preventive conservation:

- listing of the parameters of the factors threatening cultural heritage;
- evaluation of the significance of the listed safety threats;
- definition of methods to estimate the effects of these threats on cultural heritage;
- application of these methods to remove the collection safety threats. Other risk-based models for building evaluation, use the SOBANE strategy (Screening, Observation, Analysis, Expertize), a strategic approach to organize efficiently, economically, and durably the risk management [83].

Furthermore, Ashley-Smith [84] pointed out a risk assessment theory for object conservation, in order to understand the significant thresholds that may cause additional risks on buildings and objects. This approach was further developed by Michalski [75] to criticize the definition of ideal "magic numbers" for conserving the heritage.

Based on the Ashley-Smith's and Michalski's approaches [75,84], the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) followed these theories, changing the traditional standard operational schemes on HVAC systems [85,86]. In the first edition of the book, the parameter considered were temperature and relative humidity [85], while the revised edition incorporated new material on pollution [86]. Instead of rigid values, the ASHRAE introduced four protection levels with different indoor conditions and exposure durations related to the sensitivity and the fragility of artifacts. The "museum climate" is based on acceptable ranges of indoor parameters, assessing the additional risks connected with the environmental thresholds. This theory introduced the concept of "adaptive comfort" as a balance between conservative and comfort requirements. It also changed the perspective of preventive conservation, remarking the importance of environmental design and management procedures.

3.5. 2006–2016: sustainability and energy efficiency

Climate change, energy savings, and greenhouse gases reduction gave a new pulse towards a rethinking of the museum environment, to encourage the development of mitigation strategies. The "Intergovernmental Panel on Climate Change" (IPCC) founded the basis of this new field of research. Following this approach, the projects "Climate for culture" (2009–2014) and European network on Research Programme applied to the Protection of Tangible Cultural Heritage (NET-HERITAGE) (2007–2013) estimated the impacts of the climate change on historic buildings and collections in Europe. Particularly, the first defined simulation and modelling tools for damage assessment, in order to predict the influence of outdoor climate on historic buildings until 2100. Also, the Project "Identification and Registration for Cultural Heritage: Enhancing Climate Quality" (AIRCHECQ) improved advanced tools, methods, and concepts for preventive conservation, considering the sustainability of the environment (2013–2018). In parallel, the museum microclimate was discussed in important conferences (Copenhagen, 2007; Munich, 2012) focused on the impact of climate change and carbon footprints reduction.

Normally, these studies are not connected to the researches on energy audit or efficiency in existing buildings. Only a pioneering research observed the energy use and climate control in the British Museums [7], including a comparative analysis on consumption of different institutions. The costs of energy in museums was studied in deep [46], analyzing the potential savings related to the implementation of guidelines on energy management. More recently, the European legislation on energy efficiency of buildings picked up this topic, boosting the reduction of $CO2$ emissions, the rise of the share of renewable sources, [87,88], and the retrofitting of existing buildings [89]. The directives introduced only the broad principles for the intervention, leaving to the local legislation the definition of policies dealing with national studies on architectural restoration. In general, the museums placed in "listed buildings" are excluded from the application of energy constrains when they cause "significant" changes in the appearance or cultural value. On the contrary, the museums sited in "historical buildings" or new museums are entirely subject to this scheme and must have similar performance [87,88]. Literature on energy efficiency of historic buildings is very extensive, but we checked only the papers focused on museums or collections conservation. It defined procedures, tools, and technologies for energy audit [90,91,141] and retrofit [92–94]. More recently, few environmental protocols considered energy and environmental performance of building [14,95]. They are not specifically designed for museums but, particularly the "Leadership in Energy and Environmental Design" (LEED) programs, made a significant impact on new museum construction [14]. Moreover, the European Committee CEN/TC 346 [33] provided specific standards for protecting the collections, controlling the environmental variables, and implementing the energy efficiency (in this case for historic building not for museums). Recently, few publications proposed risk-based models on preventive conservation [18] or energy and environmental quality [5,16,96] in museum buildings, also considering the SOBANE strategy [75,97].

Besides environmental monitoring and technical control of indoor conditions, the museums assume an educational role for citizens and visitors related to environmental sustainability and energy efficiency. Cassar [13] underlined this dual role of preventive conservation, also related to the managerial training and staff motivation. For this reason, especially in the last decades, conferences and courses on preventive conservation in museum buildings have been developed. Topics of the conference were:

- environmental preservation of artworks (i.e. Museum Microclimates, 2007; IAQ Working Group, 1998–2015; ICOM, 2011; Precomos, 2011–2014; PCHE6, 2016; APrevU, 2017);
- effects of climate change on conservation (i.e. IIC Conference, 2008; Climate for Collections conference, 2012).

Furthermore, the "Seminars on preventive conservation and monitoring of the architectural heritage" (SPRECOMAH) founded by European Commission (2002–2006) boosted the creation of a scientific network. Finally, the courses concern the same subjects of the conferences (i.e. Getty Conservation Institute (GCI), 1990–1995; Paris I Pantheon-Sorbonne University, 1993-onwards; ICCROM, 2014; University College London (UCL), 2014-onwards).

4. Research results

To have a wide range of cultural approaches and topics, the publication are realized in different Countries, mainly in Europe (74.5%) and America (18.2%), but we considered also international publications (7.3%).

In Europe, the publication are from nine Countries: Denmark, France, Germany, Great Britain, Greece, Italy, Norway, Spain, and Sweden. In journals and conference papers we considered mainly the affiliation of the institution and/or the author for defining the provenience of the publications. On the contrary, the proceedings of international conferences (not the single paper) are related to the nationality of the institution that organizes the conference. The documents are mainly from Italy (40.2%), Great Britain (26.8%), and France (7.3%), where preventive conservation is born. Also, we found different publications in the Scandinavian area, particularly in Denmark (3.7%), Sweden (1.2%), and Norway (1.2%). Mainly thanks to two European researches dedicated to this topic [107; 108], we found a project directed by a Greek institution (3.7%). Finally, few documents in English are from Germany (1.2%) and Spain (1.2%). We detected also the European standards and directives on preventive conservation and energy efficiency of museum

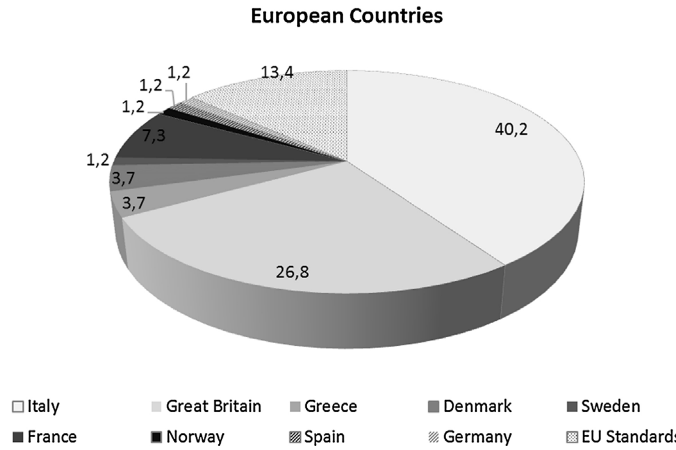

Fig. 1. Percentage of publications considered in the European Countries (%).

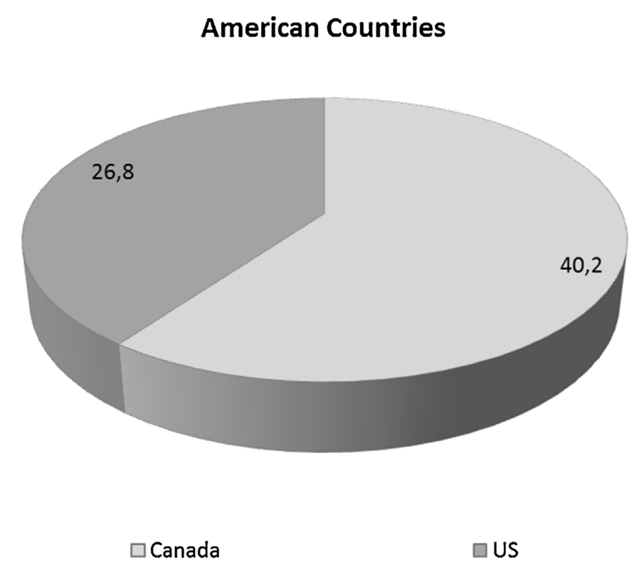

Fig. 2. Percentage of publications considered in the American Countries (%).

and heritage buildings (13.4%), which are considered with a more general European provenience (not referred to a single country). Next, the percentage of the selected publications is illustrated (Fig. 1).

In American Counties, we considered US (37.8%) and Canada (26.8%). Moreover, we studied only few publications on South American architecture realized by researches hosted by US or International institutions. Following, the percentage of the selected publications are illustrated (Fig. 2).

Referring to the periods established by de Guichen [19], we noted that the number of publications increases progressively in the last three decades (Fig. 3). Precisely, the percentages of the selected publications are: 8.2% (1965–1975); 6.1% (1976–1985); 13.3% (1986–1996); 27.6% (1996–2005) and 44.9% (2006–2016).

The literature is mainly divided in two parts:

- the first focused on scientific issues and developed by research institutes and standard committees [12,56–63,77];
- the second dedicated to operative guidelines and settled principally by museum's curators [98–100]. For this reason, we considered different types of publication, such as: books (24.5%), journal (7.3%) and conference (24.5%) papers, guidelines (22.7%), standards (14.5%), restoration charts (4.5%), and legislations (1.8%).

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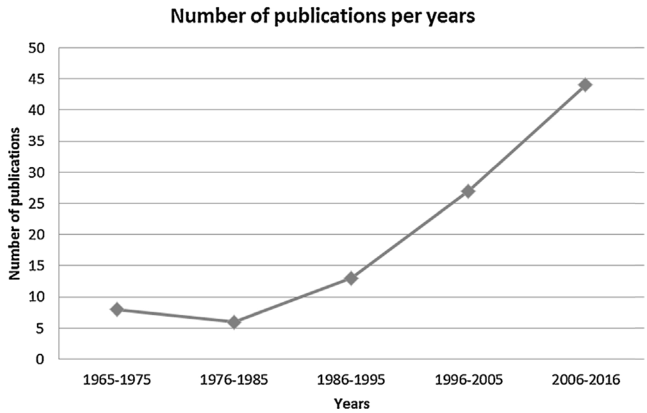

Fig. 3. Number of publications considered per historical periods defined by de Guichen's theory [19] on preventive conservation in museum buildings.

The types of publication are very different in the selected countries. In Italy, we studied mainly journal papers (30.3%) and books (27.3%), followed by conference papers (12.1%), standards (9.1%), guidelines (6.1%) and legislations (6.1%). Conversely, in Great Britain, we evaluated guidelines (45.5%), journal papers (27.3%), books (18.2%), conference papers (4.5%), and standards (4.5%). Particularly, English guidelines on preventive conservation [12,13,38,39,62,63] are considered as a reference for the museums institutions all over the world from the early history of these studies. This situation is due to the operative approach that gives clear requirements and procedures, both for technicians and museum conservators. The same situation appears for France, with several guidelines (50%) and equal percentage of books (16.7%), conference (16.7%) and journal (16.7%) papers. In US we examined books (43.8%), journal papers (31.3%), guidelines (18.8%) and conference papers (6.3%) while all Canadian publications are guidelines (100.0%). Also in this case, American and Canadian books and guidelines are considered a reference for conservators, technicians and museum staff all over the world. Following the types of American publications are reported (Fig. 4).

The documents have been realized by different type of institutions, such as research institutes (47.7%), public authorities (19.3%), museums (15.6%), standard committees (13.8%), private companies (1.8%), and European projects (1.8%).

Mainly research institutes and universities (67.7%) realize Italian publications. This situation reflects perfectly the type of publications, that are mainly books, conference and journal papers edited by scientists and researchers. Also, public authorities (15.2%) and standard committees (9.1%) have an important role for defining legislations [71], and standards [64–66,70]. Similarly, mainly research institutes (50.0%), museum institutions and associations (22.7%) realize the publications selected for Great Britain. Several important institutions and associations are active on this territory. We checked: the "Museums & Galleries Commission" [101], the "Heritage Preservation Office" [102], the "English Heritage" [103] and the "Centre for Sustainable Heritage" at the UCL [104]. This situation reflects the types of publication that are composed mainly by guidelines (45.5%), journal papers and books (35.5%). Public authorities publish all the publications selected for France. Particularly, we examined the "Direction de Musées de France" and the "Ministère de la Culture et de la Communication" [105] that printed specific guidelines with precise rules for ensuring correct microclimate, security and exhibitions. We checked also other important associations at European level, such as: the "Netherlands Institute for Cultural Heritage" [106] in the Netherlands, the Conservation Department of the "National Museum" [107] and "Indoor Air Quality in Museums Building" [108] in Denmark, the "Long Life for Art Site of Christoph Waller" [109] in Germany, and the "Heritage Conservation and Historic Preservation" [110] in Austria. Similarly, research institutes (75.0%), public authorities (12.5%), museums (6.3%) and private companies (6.3%) realize the publications selected for US. Also here, as in Great Britain, several important associations are active in the field of preventive conservation. We considered: the "American Institute for Conservation of Historical and Artistic Works" (AIC) [111], the "Conservation Science Network" [112], the "Cultural Resource Management" (CRM) [113], the "National Center for Preservation Technology and Training" (NCPTT) [114], the GCI [53], the NPS [52], the "National Preservation Institute (NPI) [115], the Bay Area Art Conservation Guild" [51]. This situation reflects the types of publication, that are composed mainly by books (43.8%) and journal papers (31.3%). Following, this situation is reported (Fig. 5).

Finally, in Canada we considered publications edited by research institutes (50.0%) and museums (50.0%). Particularly, we checked the documentation produced by the "Canadian Conservation Institute" (CCI) [50], the "Canadian Heritage Information Network Home Page" (CHIN) [116], and the "Conservation Information Network" (BCIN) [117]. Finally, at international level we observed the works produced by the ICOM [42], the ICCROM [43], the "International Committee Training of Personnel" (ICTOP) [118], and the "International Council on Monuments and Sites" (ICOMOS) [119].

5. Discussion

In these years (1965–2016), many studies have been developed on preventive conservation in museum buildings, defining a series of rules and recommendations. Summarizing these researches, its main fields of action regard:

- damage preservation and environmental management;
- architecture and exhibit design;
- environmental and energy simulations;
- monitoring, recording and controlling of the environmental agents;

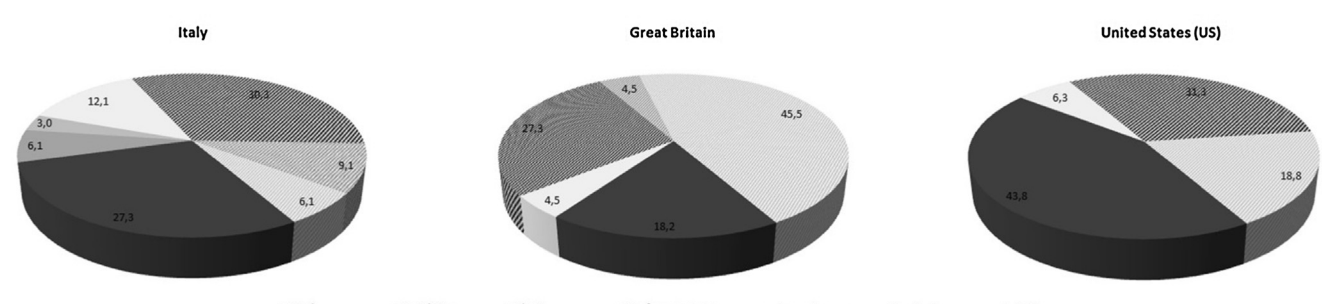

Fig. 4. Type of Italian, British and American publications considered (%).

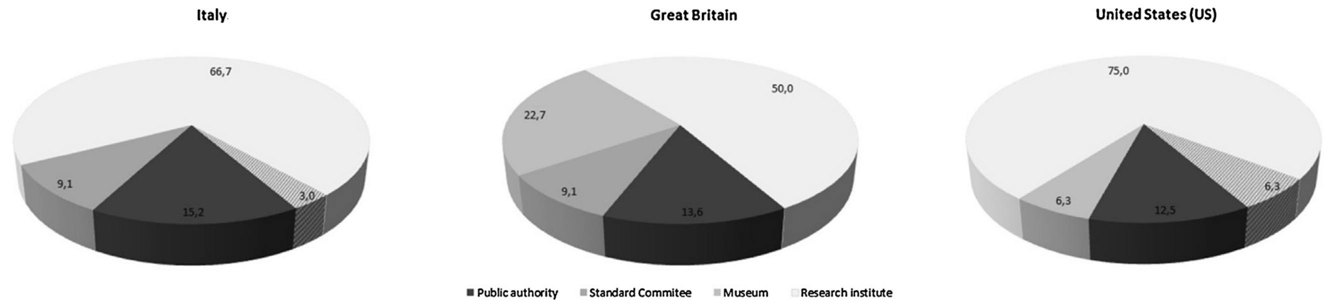

Fig. 5. Type of Italian, British and American organizations considered (%).

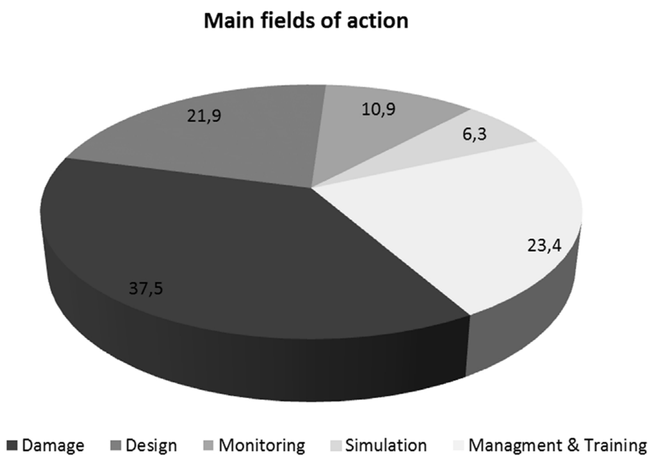

Fig. 6. Main fields of action (%).

- management and training. For each paper we define the different topics treated, and then we identify the percentage of each single key action.

The key actions outlined by the selected publications are related to damage preservation (37.5%), management and training (23.4%) and museum design (21.9%). The technical aspects of monitoring (10.9%) and simulation (6.3%) have a small role. The outcomes of this study are reported below (Fig. 6).

Damage preservation is the topic more studied in each Country (Italy: 33.5%; Great Britain: 35.9%; France: 60.0%; US: 28.6%; Canada: 50.0%), followed by management and training (Italy: 14.5%; Great Britain: 33.3%; France: 30.0%; US: 28.6%; Canada: 37.5%), and museum design (Italy: 17.7%; Great Britain: 20.5%; France: 10.0%; US:; Canada: 12.5%). Only in US, museum design (32.1%) is more considered than management and training (28.6%). Monitoring and simulation have an average rank of 10.0% per each country.

The same occurs analyzing the fields of action per year. Damage preservation is the most published topic in each historical period but decreased from the middle 1980. The number of publications on museum design increased significantly in the analyzed period. On the contrary, the ones on management and training increased only in the last decade. Furthermore, the publication on monitoring and simulation are quite recent. The first started 20 years ago, and the second only 10 years ago. The percentage of publications considered per historical periods is displayed below (Fig. 7).

5.1. *Damage preservation and environmental management*

The studies on damage preservation and environmental management regard (Fig. 8):

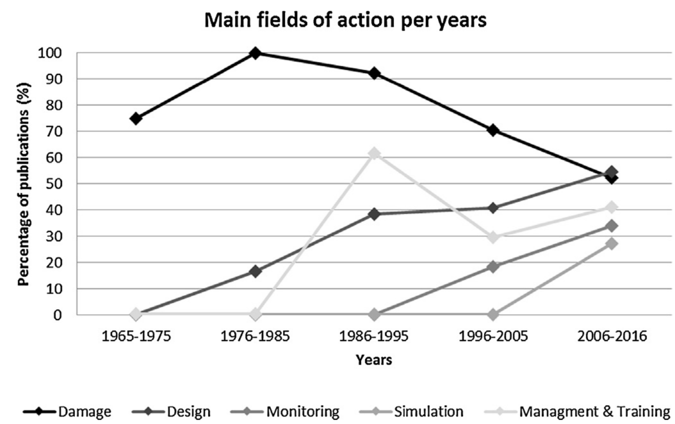

Fig. 7. Main fields of action per historical periods (%).

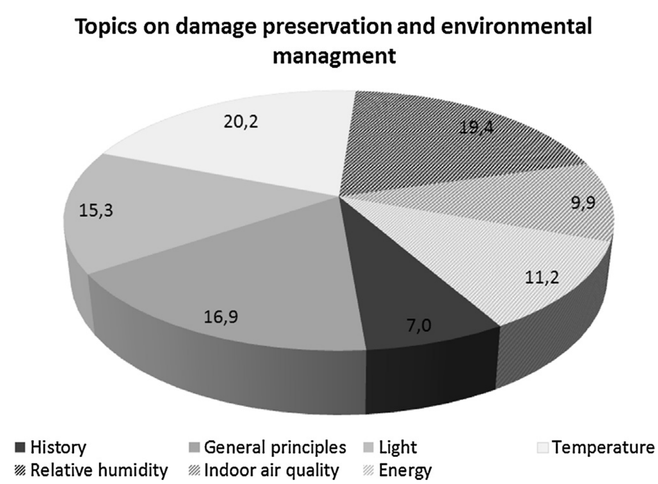

Fig. 8. Topics related to damage preservation and environmental management (%).

- history of preventive conservation;
- general principles for balancing conservation and users' comfort;
- parameters for ensuring the environmental control;
- energy.

Few publications concern the history of preventive conservation. First, de Guichen settled a critical history [19] and then, Lambert [20,21] produced a more complete historiography in England, Italy and US from the pioneering theories to the XXI century's concepts. Also, Luciani [10] proposed a historical methodology to define the indoor climate in heritage buildings, analyzing standards, researches, and cases studies. Similarly, Alcantara [78] published for the ICCROM a history of the environmental standards in museums. The documents are very useful for defining in an

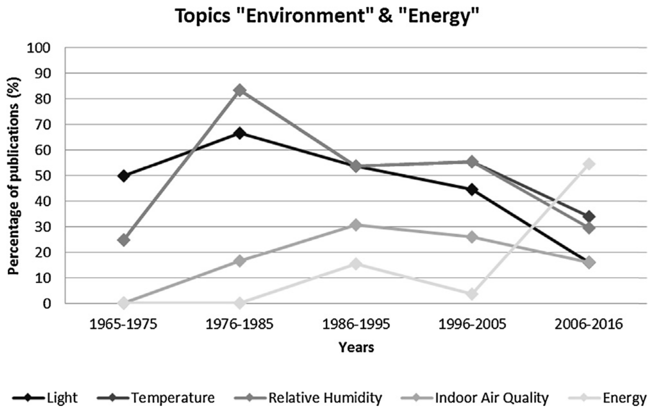

Fig. 9. Number of publications per historical period related to environmental and energy management (%).

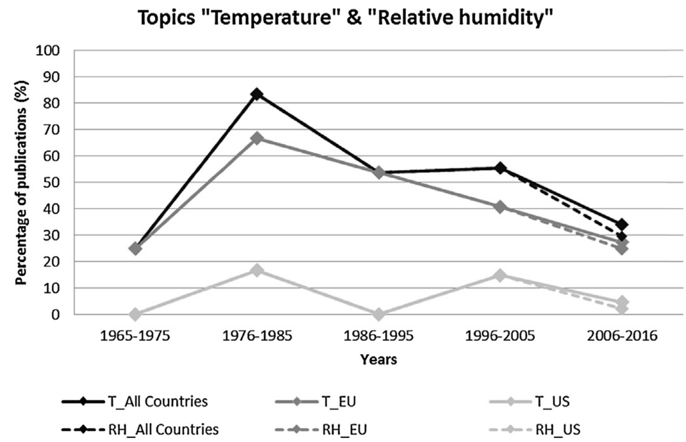

Fig. 10. Number of publications per historical period related to hygrothermal control (%).

ordinate way the milestones and the fundamentals of preventive conservation studies.

Besides, the literature treated extensively the topic related to the general principles for balancing conservation and users' comfort. The "Light" (L) aspects are the most treated from 1965 to 1975. Then, the issues "Temperature" (T) and "Relative Humidity" (RH) are extensively considered, while "Indoor Air Quality" (IAQ) has a growing interest from 1980s, especially in US and Scandinavia. The studies on "Energy" (E) arose from 2005, especially in Europe for the impulses given by the Directives on energy efficiency in buildings [87–89]. The number of publications considered on these topics in different historical periods is reported below (Fig. 9).

Initially (1975–1995), the publications on light concerned principally the criteria and the variables for preserving the collection from photochemical damage [44,45,56,57,59,120]. The presence of light, as a matter of fact, may cause important decays, as:

- yellowing, fading or color variation;
- corrosion;
- alteration and corruption;
- surface temperature increasing;
- acceleration of the deterioration.

Only later (1996–2005), the studies on environmental psychology demonstrated its central role for emphasizing the visual perception of observers [16,121]. To balance comfort and conservation, standards [13,58,122] and literature [16,59,121] consider also:

- direction and distribution of light;
- light levels;
- luminance contrasts;
- color tones;
- absorption;
- objects surface reflectance;
- "annual energy exposure" to light.

After a pioneering study on energy consumption in museum buildings [13], the energy efficiency of lighting systems is studied from the last decade (2006–2016) [13,92,93,122].

Temperature and relative humidity are extensively picked up from the first debates on preventive conservation in museums (1976–1985). Until 2005 they are treated in the same publications; next specific works on each parameter arose (Fig. 10).

Initially (1965–1975), the researches concerned physical and chemical mechanisms of decay. The variables considered are [11,35,47,49,64–66,70,73,81,123,124]: air temperature, relative humidity, ventilation rate, and air velocity. Particularly, inadequate air temperature and heat transfer may cause [35,47,49,123]:

- expansion;
- acceleration of natural damage and chemical processes;
- partial drying up;
- increasing of the fragility.

Likewise, hygrometric fluctuations may generate [11,35,47,49,123,124]:

- size and shape modifications;
- chemical reaction;
- biological deterioration.

These effects are catalyzed by low ventilation rate and high air velocity [81]. After defining the potential decays, the definition of the best hygrothermal conditions for preserving the collections has been debated for decades (1976–1995), sometimes producing harsh discussions [10]. Then (1996–2005), the literature moved on heating, ventilation and air-conditioning (HVAC) design [125]. The first studies on thermal and hygrometric comfort considered mainly the use of air-conditioning systems, both for museum buildings [47,125] and exhibits [126]. Only later (2006–2016), they concerned also passive measures [70,78,123] and HVAC control for energy efficiency purposes [9,127–130].

Similarly, initially (1986–1995) the literature [72,131–133] on pollution control considered the damage produced by hazardous gases (i.e. sulfur oxides, nitrogen oxides, ozone, hydrogen sulfide, soot, particles, formaldehyde, and volatile organic compounds), fungal attacks, and bacteria. Then (1996–2006), the implications on the environment have been studied [12,63], considering:

- outdoor environment (i.e. adjacent buildings, parking lots, vegetation and landscaping);
- internal functions (i.e. laboratories, offices, bars and restaurants);
- building features and materials (i.e. construction materials, internal finishes, furniture, exhibits, air leakage, heating and ventilation systems);
- open access (i.e. number of visitors);
- management (i.e. handling, cleaning and packaging materials and procedures).

Generally, the concept of dose (the concentration of the pollutant multiplied by the duration of exposure) is suggested to determine an acceptable rate of deterioration. Furthermore, the

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idea of "multi-pollutant" situation as an interaction among different pollutants arose, complicating the risks assessment of heritage decay [132]. Only recently (2006–2016), natural ventilation is promoted for reducing moisture, growth of microorganisms, summer energy consumption, also ensuring human comfort [70,78]. So far, a specific bibliography on acoustic comfort in the museums lacks.

The literature on the cumulative effects related to complex synergistic interactions among these parameters started from the Camuffo's theory [35] and promoted European researches, guidelines [71], and standards [64–69].

The definition of environmental standards has been deeply discussed for many years, considering all the issues related to conservation and human comfort. Also, their relationship with energy efficiency has been studied in historic buildings (generally not in museums), developing criteria, technology solutions, case studies, and so on. Now, a systemic organization of this knowledge is necessary at international level, in order to create networks, atlas, trainings activities, and so on.

5.2. Architecture and exhibit design

The studies related to architecture and exhibit design concern principally: bioclimatic and passive design; and risks connected with the use of HVAC systems. No publication regards the aspects related to renewable technologies and green energy production.

The use of passive climate control strategies is quite common in museums inside historic buildings, not only in the past [10]. Many objects survived over centuries under not controlled indoor conditions as request by existing rules and standards [11,124]. Normally, the collections acclimatized to diurnal, seasonal and annual hygrothermal fluctuations thanks to the architectural features [10,49,124]. The building design itself has seldom explored as a potential for maintain the hygrothermal equilibrium in museum rooms, due to the preservation risks connected with unstable climatic conditions [11,49,124]. Only recently (1995–2016), the effects of traditional features and materials on museum climate have been considered (e.g. natural ventilation for regulating air exchange, buffer spaces for having climate stability, curtains, awnings and vegetation for reducing heat gains, moisture-reactive wall surfaces for moisture buffering, and so on). This situation is connected with the rising of fuel prices and carbon dioxide emissions [95,126,134,135]. The writings concern mainly temperate [79,80], hot [70], and tropical climates [78], or museum exhibits [126]. Generally, it estimates an energy conservation potential for regeneration of 30–50%, using correct building design and staff training [80]. Thus, criteria and passive solutions have been produced [79,80], generating also the idea that HVAC design in historic buildings should be based on this knowledge [70,95,135].

Another important topic concerns the performance achieved by HVAC system. The debate on this topic started from 1940s, when air-condition, both central system or portable heating devices or humidifiers, are considered necessary to ensure the severe indoor conditions required by museum standards [7,11,124] and due to the enlargement of heritage categories [100], the diffusion of cultural tourism [13], and the loan constraints imposed by foreign institutions [7]. This situation generated different energy and environmental problems, especially in existing buildings. As the matter of the fact, the design of the active measures required lower costs and time than the bioclimatic strategies [123] but, at the same time, it directly affected sustainability and climate mitigation [85], involving high energy consumption [13], management costs [78], and heritage risks [13]. Particularly, several experiments [13,95,128,135] demonstrated the risks caused by HVAC systems on artifacts (i.e. stress relaxation, mechanical vulnerability, fatigue fracture, flaking, mold, blistering, dust, and so on). Also, surveys and energy audits illustrated the potential savings connected with the adoption of moderate museum standards [13]. At the same time, the reduction of energy consumption and costs involved by different thermal control strategies have been studied and tested in several case studies [9,127–130], obtaining energy savings from 40% to 77% [128,130]. Currently, there is a growing recognition that the proper choices of HVAC systems as well as their tuning and maintenance can improve environmental and energy behaviors significantly.

The use of passive and active climate strategies in museum buildings is a promising topic for developing further researches, particularly on modelling and monitoring of specific case-studies. Suitable items are:

- traditional building performances in different climates;
- environmental behavior of traditional and vernacular architecture;
- technology solutions for heritage protection and passive climate control;
- integration of HVAC systems in historic museums;
- impact of large public access on high sensible collections. In these cases, only the integration among the works of conservators, heritage authorities, architects, and engineers could develop suitable solutions for balancing heritage values and human comfort, also reducing impacts and operating costs.

5.3. Environmental and energy simulations

Since twenty years ago (1996–2016), simulation is considered necessary for predicting the behavior of new and existing buildings. First, only environmental simulation was considered (1996–2005). After, also energy simulation took interest (2006–2016).

Initially (1975–1985), the risk assessment for monuments and collections was based only on materials science and previous experiences. Then (1986–1995), several guidelines and books recognized the importance of the environmental simulation for predicting any potential damage due to indoor or outdoor climates. The European Framework Programs endorsed this topic, financing different studies on the relationship among heritage decay, environmental conditions, and climate changes, both at outdoor (Noah's Ark) and indoor (IMPACT; MASTER) levels. Initially, procedures, maps, simplified tools, and technology solutions have been developed and applied to specific case studies. Later, the milestone project "Climate for culture" developed climate-predicting simulation software (HAMBase) for collections composed by variable objects and materials. Also, research institutes and software houses produced decision-support models for the risk analysis (i.e. Analytica™), in order to verify past indoor climate conditions, natural climate fluctuations, efficacy of the technical interventions, heritage hazards, and so on.

In parallel, the literature on energy audit documented the importance of the computer-based simulations for evaluating the energy behavior of new and existing buildings [90,91,95]. The studies considered mainly historic buildings, not specifically museums. Particularly, the difficulties related to the accurate identification of the thermal properties of historic building are outlined [95,135], displaying the importance of measurement and monitoring for gathering correct input data [91,134,135]. In these cases, the model calibration is considered necessary to obtain results close to the experimental data [95,135]. On contrary, wrong estimations of thermal performances, occupants' behaviors, and operation conditions may produce an overestimation of the energy consumption, promoting substitution or energy improvement of components without any real advantage for the global energy balance [9,91,127,128].

Environmental and energy modelling of historic and complex buildings is an interesting topic for developing further studies, particularly on:

- simplified and real-times energy models calibrated on energy bills and real data;
- energy optimization schemes, considering conservation and environmental damage;
- tools for coupling environmental, energy, and structural simulations.

5.4. Monitoring, recording and controlling of the environmental agents

Environmental monitoring is necessary to avoid fluctuations that may cause irreversible and unpredictable damage and discomfort for users. The effort on this activity started from 1980s, with many experimental works made by the ISAC-CNR in Italy [17,35]. These studies involved both outdoor and indoor climates, in order to define the relationship with environmental conditions and heritage risks. Specific attention was paid to innovative procedures for measurements, data elaboration and interpretation. At the same time, English, Scandinavian, German, and American museums and institutions produced other experimental data [11,124,133]. The outcomes of these experiences were the contribution for the development of Italian [64–66] and European [67–69] standards that gave some recommendations about monitoring, processing, and summarizing procedures for considering the "historical climate" [35]. From these standards, the scientific literature defined a synthetic "performance index" that identifies the percentage of time in which the measured parameter lies within the required ranges [129,136–138]. In this way, the hygrothermal quality was evaluated on the basis of a medium/long-term monitoring, not on punctual data [18,96,136,137]. These approaches are not easy understandable by conservators, because they require specific competences for the data processing with spreadsheets or specific software. For this reason, museum guidelines specified these measurement procedures without any technical evidence [13,61,62,120]. Then, monitoring is introduced as daily activity for predicting the potential environmental risks, not only for localizing and for quantifying problems already occurred. Besides, commercial tools and software are always more innovative, compact, user-friendly, and interoperable. Thus, they deal with the museum needs of:

- respect of heritage values;
- reduction of the visual impact;
- reversibility;
- cost minimization;
- clear and easy management.

Environmental monitoring is an interesting subject for further studies, particularly on:

- innovative sensors for museums;
- experimental monitoring of traditional passive buildings for verifying their environmental stability;
- simplified and user-friendly tools and software for real-time monitoring in cultural heritage buildings.

5.5. Management and training

Management and training are very important topics from 1980s. These aspects are explained mainly in museum guidelines. They settled easy and clear decision-making schemes dedicated to museum staff and conservators. Main fields of research are:

- everyday management and vigilance;
- regular maintenance and planned conservation;
- staff education and public awareness.

The first studies (1976–1985) identified the impact of improper management and vigilance on buildings and collections, in order to develop environmental management strategies for balancing access and care [8,34]. Then (1986–2006), proper procedures for registration, handling, storage, exhibition, housekeeping, packaging, transportation, shipping techniques, and vigilance are proposed as key actions to preserve historic fabric, minimize cost and reduce maintenance [81,120,135,139].

Besides, regular maintenance and planned conservation are always considered fundamentals for the building safeguard [81]. They include both short-term and interim measures and policies to protect or stabilize the heritage (small repairs), as well as long-term actions to stave off deterioration, prevent damage, and extend its physical life (routine maintenance) [98]. More recently, their role in promoting the cost-benefit approach, both for conservation and energy efficiency purposes, has been introduced [13,16,96].

Another important field of research regards managerial training and motivation of museum staff. Particularly, American, Canadian, British and Scandinavian literature emphasized their role for reducing damage and management costs [74,75,81,140]. Furthermore, the importance of environmental information for end-users has been recognized as a practical and cheap instrument to reduce their impact on artefacts [74].

Literature outlines several management actions for implementing preventive conservation plans in museums, such as:

- trans-disciplinary working tables to design the retrofit actions;
- environmental monitoring as a daily management strategy to predict the potential environmental risks and reduce restoration activities;
- managerial training for promoting the cost-benefit approach, both on preservation and energy efficiency;
- staff motivation and awards to improve the consciousness on heritage values, reduce management costs, and energy consumptions;
- environmental information for visitors as a low-cost instrument to reduce their impact on artefacts.

6. Conclusions

The paper presents a critical review of preventive conservation in museum buildings. It summarizes the theories and the approaches spanning from 1965 to 2016, outlining the history of preventive conservation in Europe, Canada, and US. From a wide range of bibliography (more than 110 publications composed by books, guidelines, researches, and other documents), the study wants to identify recurring topics related to specific historical periods, geographical countries, and cultural approaches. Main fields of action of preventive conservation regard:

- damage preservation and environmental management;
- architecture and exhibit design;
- environmental and energy simulations;
- monitoring, recording and controlling of the environmental agents;
- management and training.

Key actions are related to damage preservation, design, management, and training, while the technical aspects of monitoring and simulation have small consideration. The idea of "cultural heritage protection" changes significantly in the last century. Progressively, the logic of “prevention” arise, considered as continuous maintenance, control and management of the heritage. Furthermore, the objects of the conservation activities move progressively from the heritage buildings and sites to the artifacts, allowing the elaboration of standards, guidelines and criteria that considers all the cultural heritage categories (i.e. sites, districts, buildings, paintings, sculptures, ethnographic artifacts, treasures, books, and so on). The consciousness of the importance of the environmental impact on cultural heritage, introduced a broad debate on the definition of the standards for minimizing the decay of collections, considering first the single factors (light, temperature, relative humidity, and indoor air pollution) and next their cumulative effects. In the recent years, the literature focuses also on damages related to the building features and materials (constructive technologies, HVAC systems, exhibits, and so on) and on environmental or energy potential of old buildings. Particularly, this last point could give less invasive alternatives to air conditioning, supporting the material conservations of historic structures. The research on damage is based on the practical experiences in museum buildings or is developed during international or national researches. This supports the production of standards, guidelines for museum conservators. The environmental parameters more considered until the XIX century are light, temperature and relative humidity. The works focuses on environmental standards, strategic design criteria, balance between conservation and human comfort, and development of tools and monitoring systems. The attention on energy efficiency starts from the last decades, as consequence of the increasing of energy consumptions. The works focuses on energy audit, modelling and retrofit of historic buildings. Generally, the energy assessment and design schemes are not specific for museum buildings. Anyway, criteria, methodologies, and technical solutions are proposed, both for passive and active strategies. Other important topics are climate change and greenhouse gases reduction that encourage the development of mitigation strategies, both at outdoor and indoor level. Procedures, tools, and software for risk assessment are other important subjects for preventive conservation, human comfort and energy efficiency in museum buildings. Also, simulation and monitoring can support the design phase, for preventing damage, validating different solutions, and optimizing the interventions. Besides, everyday management, regular maintenance, and training are considered key actions for promoting safeguard, users' comfort and energy efficiency. Another topic regards the decisive role of the building conservator in the decision-making processes, developed by the growing attention to the education role of managerial training and staff motivation activities. Finally, these theories underline the importance of the support of the national policies, especially for founding the long-term planning of the preventive conservation activities.

The analysis of the literature shows interesting topics to develop further researches. The following aspects are worthy of investigation:

- cumulative effects of environmental parameters on the damage of museum collections;
- experimental monitoring and simulations on natural climate and passive technologies for verifying their environmental stability;
- criteria and technologies for integrating HVAC systems in historic museums;
- simplified and real-times energy models calibrated on bills and real data;
- tools for coupling environmental, energy, and structural simulations in complex buildings;
- innovative sensors for microclimate monitoring in museums, to ensure reversibility, reduced impact, user-friendly approach, interoperability, and real-time data gathering;
- simplified and user-friendly tools (i.e. apps, software) for environmental simulation and monitoring to be used by conservators and museum staff;
- technologies for heritage protection and passive climate control (i.e. nano-materials, coatings, insulation materials, and so on).

The results obtained may be useful as a reference for technicians and conservators to amplify and to ordinate their knowledge in the field of preventive conservation in museum buildings.

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