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The Contribution of IoT to the Implementation of Preventive Conservation According to European Standards: The Case Study of the "Cannone" Violin and Its Historical Copy

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Abstract: One of the main goals of preventive conservation (PC) is to reduce the risk of possible damage produced by the interaction between tangible heritage objects and their conservation environments. This work aims to introduce the European standard EN 15757:2010 as a potential tool for implementing effective museum PC, and it details the potential contributions of both active environmental control and Internet of Things (IoT) technologies in this regard. An application of this strategy is proposed by means of a case study of the conservation of two historical violins, part of a small but significant museum collection in the City of Genoa dedicated to Paganini, whose value is inestimable. According to the standard, monitoring of environmental parameters was carried out for more than four years in the Paganini Hall of Palazzo Doria-Tursi Museum. A remote-control system was implemented, installing digital sensors in the room and in the two showcases. The data were continuously collected through an integrated platform for supervision, monitoring and shared management, based on web-cloud-IoT technology. The analysis of climate data and the assessment of the "historic climate" led to the installation of an active control system on the display cases of the "Cannone" violin and its historical copy. The intervention resulted in a cost-effective improvement in the conservation conditions of the two objects, with an efficient system of warning and safety alarms and a protocol of resolution actions still active and ongoing. The application of IoT systems in monitoring and controlling the indoor climate of heritage collections facilitated the care of the objects at a cost reduction for the institution.

Keywords: cultural heritage; wood; preventive conservation; Internet of Things (IoT); EN 15757:2010; sustainability; violin

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1. Introduction

Conservation of cultural heritage includes all measures and actions aimed at safeguarding tangible objects, while ensuring their material and values remain accessible to present and future generations. Preventive conservation (PC), in the broader field of conservation, can be defined as the sum of actions aimed at preventing and reducing the potential for material loss and damage in tangible cultural heritage, carried out within the context or the surroundings of an item [1]. PC is not clearly separable from other conservation actions, but it establishes a strong linkage between every object in its conservation environment. Garry Thomson, with his book published in 1978 [2], was the first to focus attention on this domain of preventive conservation, and he promoted the idea that the control of environmental conditions could minimize damage to artifacts, especially in the case of wood and other hygroscopic materials responding to both temperature (T) and relative humidity (RH) fluctuation.

1.1. Environmental Control in Heritage Institutions

The approach defined by Thomson included taking into account climate zone and object requirements to choose the appropriate environmental parameters for conservation. Nevertheless, specific and rigid values of 50% ± 5 RH and 21 °C ± 2 T were adopted by many institutions [3] and included in building plans, collection policies and loan agreements [4–6]. This trend demonstrates a world-wide effort to codify best practices in construction, handling, storage and display in spite of the likelihood that these conditions could seldom be maintained without deviation in many museums [7]. In fact, for numerous museums and heritage organizations the suggested air quality levels were unrealistic and simply unachievable in practice due to the energetic and economic costs: the control of environmental parameters at building level is very complicated, energy demanding and expensive, and it is further complicated by the nature of the collections, the nature of the existing historic museum buildings and their internal fixtures and fittings, and the continued requirements for visitor access.

Furthermore, research into the structural responses of wood, adhesive and painting materials to changes in relative humidity conducted at the Smithsonian Institution [8,9] and Canadian Conservation Institute (CCI) [10,11] during the late 1980s and 1990s showed that some types of organic materials were more physically resilient in a wider range of relative humidity than had been previously assumed: the research demonstrated that the risk associated with RH should be evaluated on an individual object basis and that the very limited range previously quoted as acceptable for many objects was often not necessary.

In 1999, the addition of climate specifications for museums, galleries, archives and libraries in the Applications Handbook of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), followed by revisions up to the latest version in 2019 [12], led to a more realistic, risk-management based approach to the choice of T and RH specifications. This approach was linked to the sensitivity of collections and the architectural setting, clearly outlining the risks associated with each choice, and addressed the issue of different climate zones and the importance of using the historic average of an institution's collection as a starting point. This approach is also the fundamental basis of the European Standard EN 15757, Conservation of Cultural Property—Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials, published in 2010 [13]. The standard provides a guide to study and evaluate the so-called "historic climate" of a collection and specific objects kept in indoor environments of museums, galleries, archives, libraries, storage areas, churches and modern or historical buildings.

1.2. EN15757:2010 and IoT System

The rationale behind EN 15757:2010 is based on the concept of "historic climate", which means that cultural objects, over time, might have acclimatized to specific environmental conditions. In the case of hygroscopic materials, and of wooden objects specifically, where RH change may generate permanent damage, it becomes potentially dangerous to move the object from its historic relative humidity range to another one, even if this new range is theoretically better. The key assumption of the standard is the assessment of the state of preservation of the object—to be carried out by curators and/or conservators. If the object reveals to be well preserved, it implies that the historic climate has been safe, and that it should be kept unchanged to avoid the occurrence of risky situations. Alternatively, in a case where the need to make corrective interventions is evident, the application of EN 15757:2010 involves the concept that a reduced variability may be beneficial while an increase may be risky. The standard abandons the approach based on limited acceptable ranges, introducing the "safe band" (SB) concept [14].

The determination of SBs according to EN 15757:2010 requires a microclimate monitoring based on, at least, one-year of data recording; that is the minimum time required for assessing if current environmental fluctuations are safely acceptable for the object. If RH variations are sufficiently small, i.e., within 10%, they can be ignored, otherwise, the belt between the 7th and 93rd percentiles of RH fluctuations is considered safe. Fluctuations that exceed the 7th percentile on both the extremes—dry and humid side—are considered out of the SB and are potentially dangerous. Therefore, SBs include the most common fluctuations, but exclude the most extreme ones, because they might trigger some micro-damage that could be revealed in the longer term. These limits of SBs should be used as target limits for the RH of the conservation environment to be controlled.

The contributions of both Information Technologies (IT) and the Internet of Things (IoT) in implementing the abovementioned goals are becoming more significant over time. The possibility to acquire and to process, even in remote modality, climatic data concerning museum or exposition environments represents a powerful instrument for museums and collection curators. Developments in sensor and data transmission technologies make environmental data more widely available, allowing the achievement of the requirements of international standards (i.e., EN 16242, Conservation of cultural heritage—Procedures and instruments for measuring humidity in the air and moisture exchanges between air and cultural property, 2012 [15]). The introduction of target limits and warning signals can be easily done using an IoT approach; this involves the installation of small IoT sensors near the objects and environment gateways for data transfer to the cloud. This approach allows online monitoring and continuous supervision with easy access from the cloud to data recorded from sensors, improving PC and safety for the object. Such systems optimize resources and avoid expensive in situ installations, allowing massive supervision of artefacts in museums or historical buildings together with the definition of critical thresholds that can indicate potentially dangerous situations to those in charge of conservation [16]. The latest developments in IoT technologies make it potentially possible to provide almost any space, and certainly any showcase or storage area, with specific environmental parameters, at affordable cost investments.

It is important to remark how crucial the decision-making process is for PC and for the application of modifications to the environmental conditions. In these instances, the decision-making process is extremely challenging [17], requiring a multidisciplinary collaboration between scientists and conservators. The choice of potential changes in the environment must be supported by a precise knowledge of the collections, individual objects, and their history. This is possible through teamwork and a collaborative decision-making process, as demonstrated in the case study presented in this paper. Here, the technological developments described above were applied in order to improve the conservation environment and the risk-management plan on two precious historical objects on display in a museum.

2. Materials and Methods

The present research proposed a case study that deals with the conservation of the historical violin "Cannone" ("Cannon", in English). The violin was made in 1743 by Giuseppe Bartolomeo Guarneri (1698–1744), who is considered to be "one of the two greatest violin makers the world has so far seen". Giuseppe, known as "del Gesù", crafted the instrument in his studio in Cremona (Italy), "the greatest of all violin making cities" [18] (p. 17). The violin was played by Niccolò Paganini for much of his career, one of the most important violinists and composers, and he named it for the power of its sound. At his death, the violinist bequeathed his prized instrument to the town of his birth, the city of Genoa, where it is now exhibited in the Palazzo Doria-Tursi Museum, part of Genoa's museums of "Strada Nuova", opened in May 2004 when the city was the European Capital of Culture. In the same room, dedicated to Paganini, another violin is conserved: the 1834 "Cannone" copy by Jean-Baptiste Vuillaume (1798–1875), donated by Paganini to his pupil Camillo Sivori (1815–1894) and upon his death to the city of Genoa. This violin is now known as the "Sivori". The Paganini Hall also presents other memorabilia that belonged to the violinist, such as letters, sheet music, a portrait by Paul de Pommeyrac (1807–1880) and a statuette by Jean Pierre Dantan (1800–1869) [19].

The "Cannone" and "Sivori" violins are on display in two identical cases (Figure 1).

Figure 1. The Cannone exhibition case, in the room dedicated to Paganini in Palazzo Doria-Tursi Museum (Genoa, Italy). From http://www.museidigenova.it/it/content/teca-espositiva (accessed on 9 February 2021).

The uniqueness of the Cannone violin lies both in its cultural and historical value and its conservation state: it is one of the two only violins by Guarneri "del Gesù" intact in all its principal parts, and one of the best preserved in the world, but the only one played by Paganini throughout his career. The violin is still played on cultural events that enhance the different elements that characterize it, not only and exclusively the acoustic aspect of the instrument but the historical, cultural value of Paganini and Guarneri "del Gesù".

Previous studies on this masterpiece had the goal to model [20] the violin in order to identify its structural [21], hygroscopic [22] and rheological behaviors [23]. In order to develop a hygroscopic model of the violin during use, a series of environmental and mass measurements were recorded during concerts, evidencing that violin mass variation depends mainly on environmental conditions and that the role of the player is negligible [24].

In this wider project, the climatic characterization of conservation environments was planned according to two different steps: a first phase focused on experimental surveys and climate monitoring for the identification of the SBs on the two objects according to EN 15757, and a second step focused on the definition and validation of the adequate RH levels to the PC of the violins through the installation of a control system and real-time monitoring using IoT nodes.

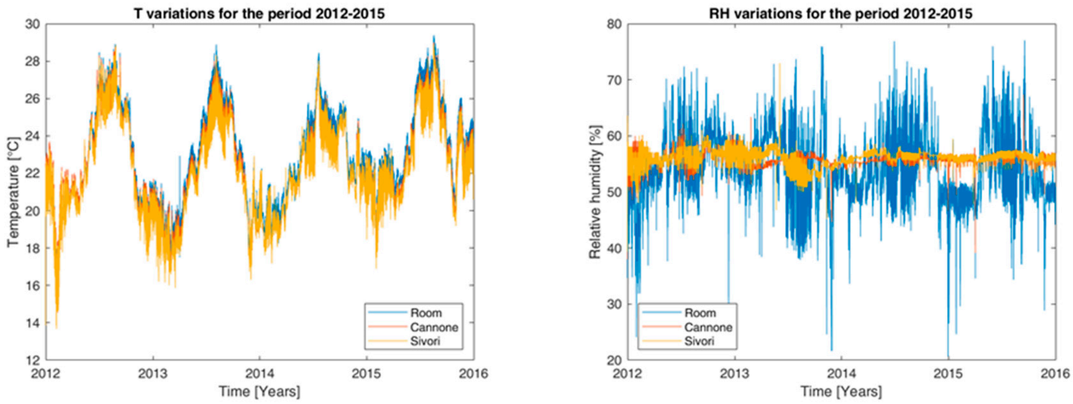
For the first step of the research, RH and T inside the conservation showcases were monitored by a Rotronic Hygroclip probe (accuracy $\pm$1.5% and $\pm$0.3 °C, respectively), and data were acquired through LABview software every 30 min. This step served to survey the climate condition of the room—where two humidifiers, set to the historic humidity average, were and are still present—and of the two cases—with two PROSorb silica gel cassettes as a passive RH control system.

Later on, a remote-control system was implemented. URT C310 CEAM digital sensors (accuracy $\pm$2% and $\pm$0.5 °C) were installed in the room and in the two showcases, with a sampling interval of 10 min. The data were continuously collected through the CEAM CWS software, an integrated platform for supervision, monitoring and shared management, based on web-cloud-IoT technology [25]. The platform allows the real-time monitoring of the data and the use of warning and safety signals in the case of an unfavorable emergency occurrence. The data collected have been elaborated through MathWorks MatLab computing environment, using a customized data code created according the EN 15757:2010 Annex A [13].

In February 2013 and in September 2013, respectively, humidity active control systems on the Cannone and on the Sivori display cases were also installed: two Preservatech PMCG active microclimate generators were used. The chosen device is a humidity generator based on solid-state technology that does not require filling or emptying of reservoirs or any other regular maintenance [26]. This instrument is relatively inexpensive on the market and has a 30 W power consumption.

3. Results: The Climate Monitorization in the Paganini Hall

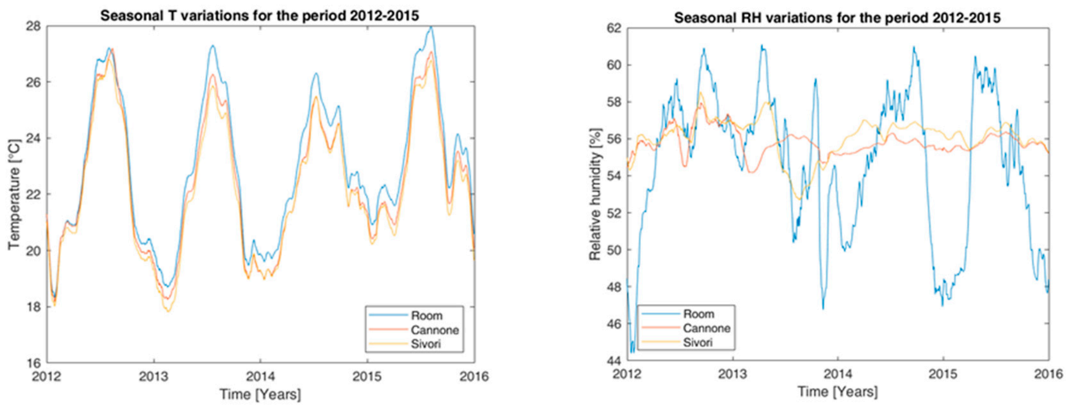
The data collected in the period that spans from January 2012 to December 2015 for the room and for both the Cannone and the Sivori display cases are shown in Figure 2.



(**a**) (**b**)

Figure 2. Variations of (**a**) temperature (T) and (**b**) relative humidity (RH) over time for the period January 2012–December 2015 for the three locations monitored: room, Cannone and Sivori display cases.

Average levels of RH were determined and statistically represented in terms of seasonal cycles obtained by calculating, for each reading, the central moving average (MA) (the arithmetic mean of all the RH readings taken in a 30-day period composed of 15 days before and 15 days after the time at which the average is computed). MA smooths out the short term fluctuations and highlights longer-term trends or cycles. The seasonal variations of T and RH are presented in Figure 3.



(**a**) (**b**)

Figure 3. Seasonal variations of (**a**) T and (**b**) RH over time for the period January 2012–December 2015 for the three locations monitored: room, Cannone and Sivori display cases. The arrows indicate the installation of the control system on the two showcases (February 2013 on Cannone and September 2013 on Sivori).

The temperature values in the graph show seasonal fluctuations over the years, in the range of 18–28 °C. These values are caused by the normal fluctuations of the building environment and its seasonal changes, which is not very insulated from the external fluctuations. The values of the two showcases are very similar to the room values, due to the minimal containing effect of the cases on the temperature variations. The T fluctuations for the two violins are considered not to affect the conservation state of the objects, apart from their influence on RH variability.

In fact, the relative humidity values of the room vary according to temperature fluctuations and seasonal changes over the months, in a range of approximately 45–60%. However, the RH values directly measured on the two violins are less variable, thanks to the display cases containing effect, especially after the installation of the control system in 2013.

Reference Year before the Intervention—2012 Climate Data

On RH data of the year 2012, before the installation of a control system, short term fluctuations were calculated as a difference between a current RH reading and a 30-day MA. Thus, it takes into account both the natural seasonal variability and the stress relaxation time constant of the materials. The parameter T is not directly considered in this analysis, if not for its influence on RH fluctuations.

Short term fluctuations for the three measured points are shown in Figure 4.

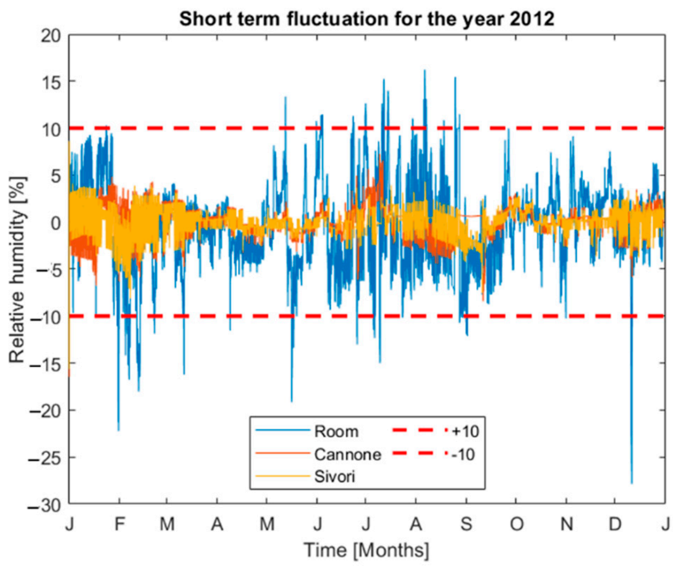


Figure 4. Short term fluctuation for the year 2012 for the three locations monitored: room, Cannone and Sivori display cases. The graph shows also the ±10% fluctuations limits described by EN 15757:2010.

The graph shows that the room RH fluctuation exceeded ±10% many times during the year, resulting in an unacceptable variability, due to the limits of the humidity control system present at the time.

On the other hand, RH fluctuations of the two showcases were less variable, but with possible improvements. While the values of RH and its fluctuations revealed an instability of the climate in the room, the cases, which are equipped with silica gel cassettes, had a sufficient containing effect to prevent extreme fluctuations, but with margin for improvement. Therefore, the installation of the control systems directly within the showcases was planned.

Yearly average and the target limits described by the EN 15757:2010 (7th and 93rd percentiles) have been calculated for the three sets and are reported in Table 1.

Table 1. Determination of the RH safe band as explained in EN 15757 annex A for the reference year before the intervention 2012.

Location	Yearly Average	7th Perc	93rd Perc
Room	55.2	−6.4	6.7
Cannone	56.2	−2.7	2.2
Sivori	56.3	−2.2	2.4

4. Discussion: The Implementation of the Control System on the Cannone and Its Copy

The time fluctuations and the data limits in Table 1 were used to set the target for the control system installed. The PMCG levels were set according to the RH yearly average on 56% for both cases, while the 7th and 93rd percentiles of the fluctuations recorded in the monitoring period were used as RH lower and upper limits for the warning alarms on the IoT platform, to inform museum and research staff of any unsafe events.

Various data could be used to compare the reference year before the intervention (2012) with the new showcases environmental data after the adoption of active control. However, data from the year 2013 were not useful because the active control was implemented during that very year. One data set between 2015 and 2016 was chosen as a function of the correlation coefficient of the relative humidity signal with the reference year 2012; the correlation coefficients resulted with values of 0.3583 and 0.3545, respectively. The year 2015 was then chosen to be compared with the reference year 2012.

Year of Comparison with the Reference Year—2015 Climate Data

The data of the year of climate monitoring after the introduction of the control system (year 2015) are shown in Figure 5.

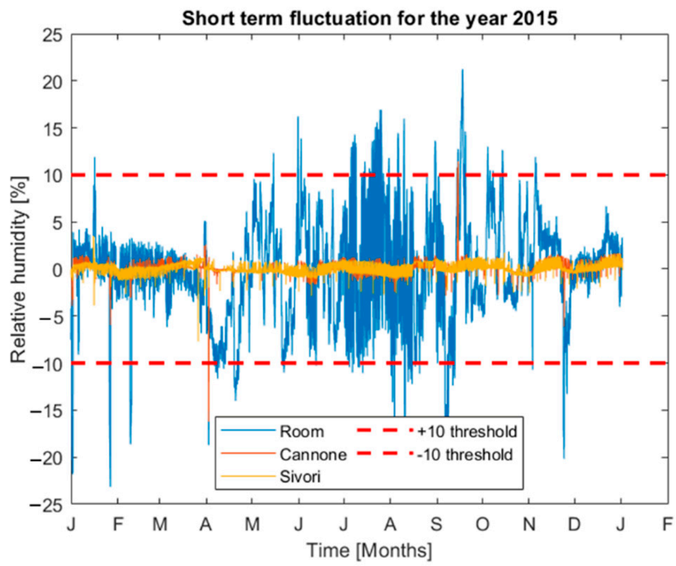


Figure 5. Short term fluctuation for the year 2015 for the three locations monitored: room, Cannone and Sivori display cases. The graph shows also the ±10% fluctuation limits described by EN 15757:2010.

As for 2012, the graph shows that the room RH fluctuation exceeded ±10% many times during the year, resulting in an unacceptable variability. The two cases of RH data displayed far less variance, thanks to the efficient control system.

Yearly average, minimum–maximum range and the target limits described by the EN 15757:2010 (7th and 93rd percentiles) have been calculated for the three sets and are reported in Table 2.

Table 2. Determination of the RH safe band as explained in EN 15757 annex A for the monitoring period after intervention (year 2015).

Location	Yearly Average	7th Perc	93rd Perc
Room	53.4	−8.4	8.0
Cannone	55.8	−0.4	0.6
Sivori	56.1	−0.7	0.9

In comparison to 2012, 2015 resulted in a much more variable RH in the room (±8.4% for 2015 versus ±6.7% for 2012), while the two showcase percentiles fell within a much lower variation compared to 2012 (±0.9% for 2015 versus ±2.7% for 2012). Moreover, the average of the two cases stayed on the level set for the instruments.

5. Discussion: The Alarms Set-Up

As the remote-control system was set up, a logic of warnings was also implemented. The warning signals were directed to the museum staff—particularly to the person in charge of the conservation of the violins, who was to be informed about the occurrence of any potentially unsafe events.

At the beginning, while the active control was not yet adopted, an alarm threshold on room RH was set at ±5 from the average humidity (55%). The alarm procedure started two hours after the threshold was exceeded (activation delay), in order to filter out any short term transient problems such as the opening of a window in the room. It was noticed that if this threshold was exceeded at the lower level this was usually caused by missing water in the room humidifiers, a problem easily solved by the museum staff, but that still required an intervention protocol and training. Moreover, an RH alarm was set with ±10% threshold from average and activation delay of 30 min, in order for the curators and conservators to be informed of relevant problems in the room. Stricter thresholds were set for the conservation/display cases.

After the introduction of the active conditioning system for the conservation/display cases, a stricter alarm policy for the showcases was adopted to promptly highlight any malfunction. The two humidity generators introduced do not require any regular maintenance, so the museum and conservation staff do not need to regularly check the machines functioning directly on site, but can instead rely on remote monitoring and the alarm policy, based on an IoT-focused approach. In fact, with the system installed, even if not yet implemented, it could also be possible to monitor the status of the machines and record relevant events such as the missing water in the adiabatic humidifier in the room or the malfunction of any machine. Other active strategies for critical cases could also be implemented.

6. Conclusions

The system that was introduced in Palazzo Doria-Tursi Museum, in the Paganini Hall, is based on a remote monitoring and decision system. The use of RH and T data collected remotely is the foundation for the control system implemented and is based on an IoT integrated system in agreement with rules established in EN 15757. The system, once installed, allowed the monitoring and characterization of the environmental fluctuations inside the exposition room and the effect of passive control with silica gel cassettes inside the conservation/display cases.

The definition of the safe bands (SBs) helped to introduce alarm logics with immediate feedback to the conservators. The system also revealed that the conservation conditions could be improved. An active climate control for the conservation/display cases was then introduced and successfully validated. Alarms and emergency escapes were planned; real-time remote access to the data was given to the museum staff and conservators.

The conservation conditions of the two violins improved thanks to the introduction of the active control system and to the remote monitoring of the situation inside the Paganini Hall. The system is still in use, and its functioning method has been considered acceptable and reliable during the last 5 years, with a sustainable methodology that allows the saving of energy and resources. The alarms are still managed by the museum staff. A total of 5844.3 EUR was borne by the City of Genoa and has demonstrated cost effectiveness, considering how significantly it has reduced the risk of potential damage to the violins associated with the environmental conditions of the two display cases.

A future implementation of the system could include the real-time monitoring of the status of the machines and other active strategies for critical cases. Further developments on the data collected and acquired by the system could include a training course for museum operators and conservators on the use of the monitoring system and its updates, providing a useful tool to support their work and the development of guidelines for proper conservation.

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