Self-adaptive dynamic indoor climate control for museums, archives and libraries. Vast energy savings at Hermitage Amsterdam museum

Rick Kramer [a, b], *Marco* Martens [c], *Edgar* Neuhaus [d]

[a] Eindhoven University of Technology, Eindhoven, the Netherlands, r.p.kramer@tue.nl.

[b] DYSECO B.V., Rotterdam, the Netherlands, r.p.kramer@dyseco.nl.

[c] DYSECO B.V., Rotterdam, the Netherlands, m.h.j.martens@dyseco.nl.

[d] DYSECO B.V., Rotterdam, the Netherlands, e.neuhaus@dyseco.nl.

Abstract. The indoor climate in museums usually is conditioned strictly to the “golden standard” of 21˚C and 50%RH. It is evident that strict climate control hinders sustainability targets, but also hinders a robust long-term preservation practice. Research at Eindhoven University of Technology (2012-2017) has yielded the concept of dynamic indoor climate control for heritage institutions and its energy saving potential has been validated rigorously. In 2019, the spin-off DYSECO further developed this concept to a control-module that can communicate with any type of Building Management System. The algorithm of the controller calculates optimal adjustments to setpoints for temperature and RH adhering to the boundary conditions set by the user, considering limits and permissible rates of change of temperature and RH. The Hermitage Amsterdam museum has played a vital role in the research and development since 2014 and employs the DYSECO control solution in all exhibition spaces since 2020. Energy data is presented based on 5 years of high-quality data acquisition. The positive effects on collection preservation due to mitigated risk under HVAC failures are demonstrated using state-of-the-art dynamic building simulations with dynamic collection damage models.

Keywords. Climate control, museum, energy efficiency, sustainability, dynamic setpoints.
DOI: https://doi.org/10.34641/clima.2022.305

1. Introduction

For the safe-keeping of collections, one of the main parameters is to create a proper temperature and relative humidity. The indoor climate can pose risks to the collections for multiple reasons: i) an incorrect climate may lead to biological degradation, eg. mould growth; ii) an elevated temperature or relative humidity can lead to a faster rate of chemical degradation and iii) fluctuations in both temperature and relative humidity may cause materials to shrink and expand, eventually creating mechanical damage. Because of the advancements in technology, the general notion has been for a long time: if 50±5% RH is good, 50±3% RH must be better.

One of the major triggers of reducing the range in indoor climate conditions was the evacuation of artifacts during WW2. The London museums moved their collections into caves which have a very constant climate. Restorers, who also moved from London to the caves, noticed that the work they had to do diminished over time: no new damage occurred to the artifacts. So, a constant climate was considered beneficial for preservation purposes [1].

In the 19th century, heating for thermal comfort was adopted in many institutions and governmental buildings, including museums. A comfortable environment became available; e.g. many museums started to exploit cloakrooms and increased temperature even further [2]. Figure 1 illustrates the evolution of the indoor climate in cultural heritage institutions in the 20th century.

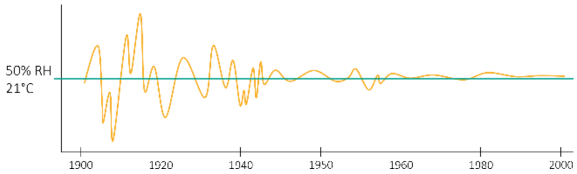


Fig. 1 – Illustration of how the indoor climate became stricter in the 20th century with less fluctuations around the ‘golden standard’ of 21˚C and 50% RH.

A few problems arose from this increasingly stricter paradigm on indoor climate control. Most museums are housed in historic buildings, with a quality of building envelope not suitable for having a constant indoor climate all year round. In climate regions with substantial seasonal variations in outdoor climate, like in western Europe, the indoor air needs a lot of humidification during the heating season to maintain the often desired 50% RH. In historic buildings this often leads to surface condensation, causing mould growth in corners and on window sills, and in case of extensive condensation even wood rot is observed.

Also, climate systems consume a lot of space within the building. Attics and basements are filled with HVAC systems, while ducts and piping run through the entire building. This often negatively affects the integrity of historic buildings.

In the 21st century, sustainability and energy reduction has become increasingly important in the built environment. This conflicts with the existing situation in many museums. Strict climate control leads to excessively high energy demands, while options for historic buildings to reduce energy losses are limited, e.g., insulating the exterior façade is not possible and insulating the interior side often leads to moisture related problems.

One effective way to address the above described issues related to strict indoor climate control is to move from the 'ideal climate' to an appropriate climate' in which limited short-term fluctuations and seasonal variations are allowed [3]. In the last 15 years, many research projects have led to new insights which have resulted in more sophisticated indoor climate requirements, e.g. published by ASHRAE [4]. Kramer et al. [5] have studied and developed energy efficient climate strategies based on the ASHRAE climate classes and integrated thermal comfort requirements. This concept of dynamic climate control determines the optimal course of temperature and relative humidity over time, respecting collection preservation and comfort, at the lowest energy demand possible. However, most building management systems are not suitable to employ dynamic setpoint adjustments. Hence, the spin-off DYSECO has been founded to develop the concept further to an add-on controller that can connect to any Building Management System. Consequently, the advantages of dynamic climate control have become available to the field of cultural heritage. In 2020, the Hermitage Amsterdam museum installed DYSECO controllers at six air handling units for their exhibition spaces. This paper compares the performance of the dynamic climate control mode versus the reference climate control mode, i.e. fixed setpoints of 21˚C and 50% RH. The effects of dynamic climate control, i.e. gradual adjustments of setpoints for ambient air temperature and RH, are evaluated on thermal comfort, collection preservation and energy efficiency.

2. Research method

2.1 Case study Hermitage Amsterdam

The Hermitage Amsterdam Museum played a crucial role in the PhD research of Kramer [6]. The main reasons this museum was chosen were symmetry (left and right wings are identical, in terms of construction and climate systems) and it was state-of-the-art in terms of building physics and HVAC systems, being completely renovated in 2007 – 2009. The historic façade had been insulated, double glazing had been introduced and air tightness had been improved. The all air climate control system was very modern too, with ground cold and heat storage (Aquifer Thermal Energy Storage). The setpoints were 21˚C and 50% RH all year round.

2.2 Measurement setup

The indoor climate and energy demand have been monitored since June 2014 until September 2021. For a comprehensive overview and explanation of the case study museum and the measurement campaign, we refer to a prior publication by Kramer et al. [7]. In summary, for the analysis in this paper, data of the following measurements at the air handling unit have been used: Electricity consumption of the steam humidifier and electricity consumption of the fan, water mass flow rate through the cooling coils and heating coils, water inlet temperature and water outlet temperature of cooling coils and heating coils. All measurements have been logged at a sampling rate of 30 s. From these measurements, the thermal power was calculated for heating, cooling, and dehumidification (sub-cooling).

The reference or 'strict mode' data set, i.e. in which the indoor climate was maintained at 21˚C and 50% RH, has been compiled from the following periods: December 2014 – February 2015 (Winter), March – May 2015 (Spring), June – August 2015 (Summer), September – November 2015 (Autumn). The 'dynamic mode' data set, i.e. in which the indoor climate was controlled via dynamic setpoints, has been compiled from the following periods: December 2020 – February 2021 (Winter), March – May 2021 (Spring), June – August 2021 (Summer), September – November 2021 (Autumn). Although the outdoor climate was not exactly the same, both periods show similar conditions and can therefore be compared. In the dynamic mode, a custom climate class was employed which could be best described as ASHRAE class A1+: Absolute minimum RH = 40%, absolute maximum RH = 60%, permissible short-term RH-fluctuations = ±5% (implemented as a maximum range between upper and lower limit), and the range was allowed to move between the absolute maximum and minimum RH at a rate of 5% per month. Moreover, absolute minimum T = 18˚C, absolute maximum T = 24˚C, permissible short-term T-fluctuations = ±2˚C (implemented as a maximum range between upper and lower limit), and the range was allowed to move between the absolute maximum and minimum temperature at a rate of 2˚C per week.

The thermal energy demands as calculated from the measurements have been divided by generation and distribution process efficiencies to estimate the consumed electricity: the heat pump's COP of 4 for heating, EER of 3 for deep cooling, and an equivalent COP of 25 for high temperature cooling, directly from the Aquifer Thermal Energy Storage. Furthermore, the energy demand is presented as average electricity consumption per week in Winter, Spring, Summer and Autumn.

2.3 Comfort and collection preservation

In a previous study [8], questionnaires were used to ask visitors how they perceived the indoor climate to develop thermal comfort limits for the museum environment. During the course of the project, over 1,250 questionnaires were filled in. The indoor conditions in both strict mode and dynamic mode were evaluated using these adaptive temperature limits.

To assess the effect of the indoor climate conditions on the preservation of objects, the specific climate risk method was used as developed by Martens [9]. The measured indoor climate was assessed with damage functions to find out whether the preservational qualities of the indoor climate were appropriate.

3. Results

3.1 Energy demands

The energy put into the building by the HVAC systems is shown in figure 2; the total values are displayed in table 1. The reference case (REF) uses on average in between 5.270 and 6.200 kWh each week, while the dynamically controlled case (DYSECO) uses in between 1.880 and 4.950 kWh each week. The savings are smallest in Summer (650 kWh weekly, a reduction of 12%) and highest in spring (4.250 weekly, a reduction of 69%). On average, over the whole year the energy demand is reduced with 51%.

When looking at the seasons individually, in Winter a lot of heating energy is saved by lowering temperature, but also humidification was reduced.

Tab. 1 – Total energy demand (kWh/week) per season

	Winter	Spring	Summer	Autumn
REF	6.200	6.180	5.600	5.270
DYSECO	2.550	1.930	4.950	1.880
Reduction	3.650	4.250	650	3.390
Reduction	59%	69%	12%	64%

Because of the lower temperature, the museum is less likely to overheat when many people enter the museum simultaneously, so also on cooling energy a bit is saved. In Spring, heating is hardly needed and also cooling is not needed very often, letting temperature free float for a reasonable amount of time. A bit more humidification is needed, but dehumidification is hardly needed. Both can be explained by an indoor temperature that matches better to the outdoor conditions.

In Summer, because of the higher indoor temperatures in the DYSECO case, more cooling is needed to prevent overheating when visitors are present. Nonetheless, much less dehumidification compensates for this. In Autumn, also a lot is saved on dehumidification and also on heating and cooling.

Tab. 2 – Total electricity use (kWh/week) per season

	Winter	Spring	Summer	Autumn
REF	3.350	1.880	2.220	2.500
DYSECO	1.980	1.480	1.700	1.210
Saving	1.370	400	520	1.290
Saving	41%	21%	23%	52%

Whereas Figure 2 shows the air sided energy demand, Figure 3 shows the related electricity consumption from the air handling processes. Also, table 2 shows the summation of electricity needed. Now, the systems efficiency for each separate step is incorporated, thus leading to purely electrical energy needed.

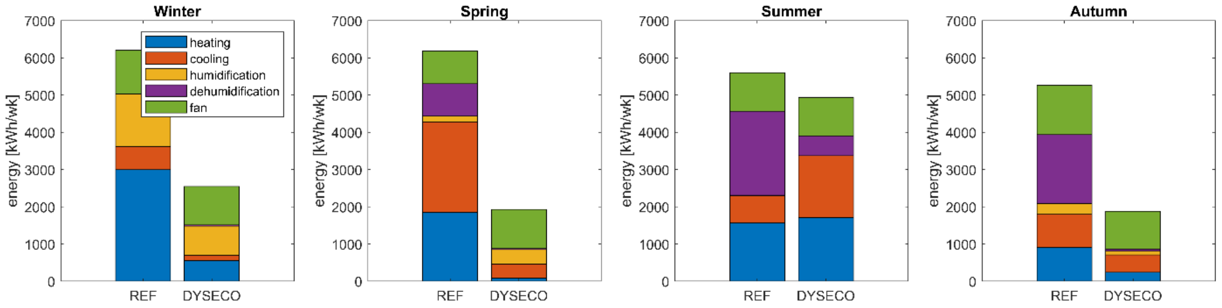


Fig. 2 – Energy demand for each season, for the reference (REF) and dynamically controlled case (DYSECO). Heating is displayed in blue, cooling in red, humidification in orange, dehumidification in purple and fan energy in green. It is expressed in kWh per week; the energy demand is the energy distributed to the air by the HVAC system

When comparing figure 2 and 3, it can be noticed that heating and cooling seem to consume less energy in figure 3 than in figure 2. This is because of the highly efficient ground cold and heat storage. In order to cool or heat, only a small electric pump needs to run to extract the desired amount of cold or warm water from this storage. So, this saves energy compared to an air-to-water heat pump. Humidification and dehumidification are less efficient, because either low water temperatures are needed (lower than the cold storage can supply) or water needs to be evaporated electrically. Also, the fan's electric energy, makes up a greater part than before.

In total an energy reduction of 36% was realised over an entire year. In autumn and winter, savings are highest (52% and 41%), in spring and summer lowest (21 and 23% respectively). Because of the efficiency of the systems, even a seasonal change in the savings can be noticed. Mind that the savings presented in figure 3 are the savings that also reflect the costs savings for the museum.

To further optimize efficiencies, it is advisable to look at methods to more efficiently run the fans and humidification systems in order to improve the sustainability even further.

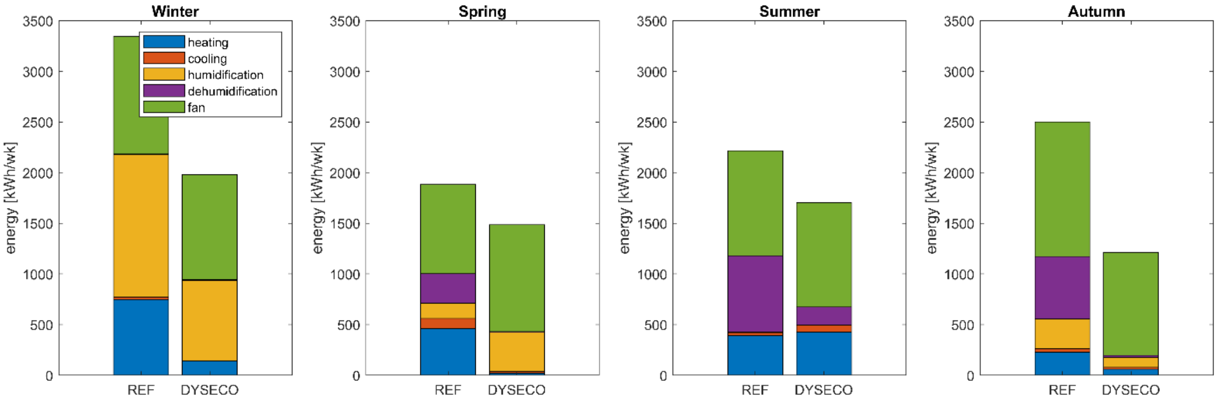


Fig. 3 – Energy consumed by the HVAC systems for each season, in which efficiencies are included. The graph shows electrical energy used. Important to note: because of the ground cold and heat exchanger heating and cooling only require electrical pumps to run during much of the period, leading to a high efficiency. This makes the fan stand out negatively, while in most museums this is only a minor energy user

3.2 Indoor climate comfort

Figure 4 and 5 illustrate the thermal comfort evaluation. Horizontally the outdoor running average temperature over three days is presented; this is the period needed for people to adapt to the weather and e.g. match their clothing. Vertically the indoor temperature is indicated. The areas in blue represent a slightly cool (light blue), a cool (middle blue) and cold (dark blue) sensation. Similarly, an orange colour indicates a slightly warm (light orange), warm (middle orange) and hot (dark orange) experience. The white area is perceived as comfortable by 95 % of all people [8].

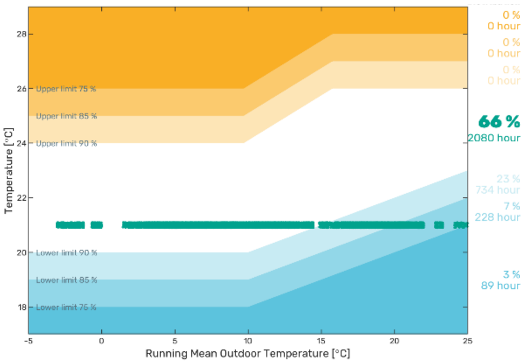


Fig. 4 – Comfort assessment for strict mode data

The questionnaires show that especially during summer the indoor climate was perceived as cool or even cold in the strict control case; 21 °C is experienced as being too low [8]. Figure 4 also indicates this: the green measurement data goes into the blue zone at higher outdoor temperatures.

It makes sense to adjust the setpoint for temperature to follow the outdoor conditions, as was automatically done during the dynamically controlled case. Now temperatures are much more into the neutral (white) zone, as can be seen in figure 5, 73 % of the period temperature was perceived as being neutral or slightly cool, as compared to 66 % during strict control.

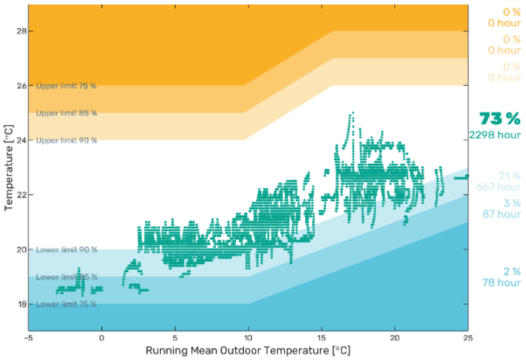


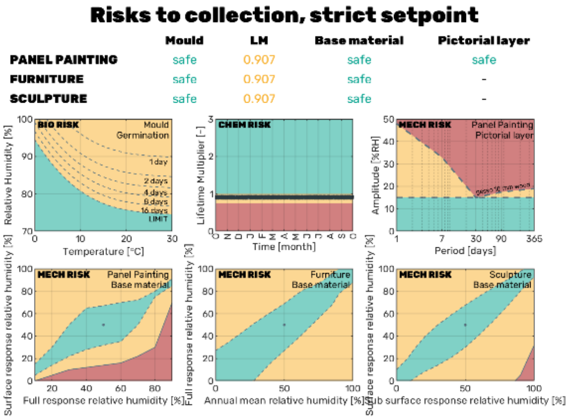
Fig. 5 – Comfort assessment for dynamic mode

More importantly, slightly cold and too cold periods were halved (from 10 % to 5 %).

3.3 Risks for heritage collections

In many museums the ASHRAE climate guidelines are being used [4]. These guidelines, developed by the American Society of Heating, Refrigeration and Air conditioning Engineers provide several climate classes, from strict to basic, each class is associated with some risks for collections. The top classes, AA and A, pose very little risk to almost all museum objects, except for very sensitive ones. AA is considered to be optimal and is meant for long term storage, while in reality many museums strive for AA in their exhibitions while class A would also suffice.

Degradation risks for common museum collections can be calculated from temperature and relative humidity data using specific degradation risk tools [9]. Figure 6 and 7 show the risks calculated for the reference case and dynamic case, respectively. At the top, mould, LM (Lifetime Multiplier), base material and pictorial layer are mentioned as indicators for biological, chemical and mechanical degradation. For three types of objects the risk is presented. The object can be safe (green), have a small risk for degradation (orange) or a high risk (red). In figure 6 only a small risk is noted for the Lifetime Multiplier, which indicates a somewhat higher speed of chemical deterioration.



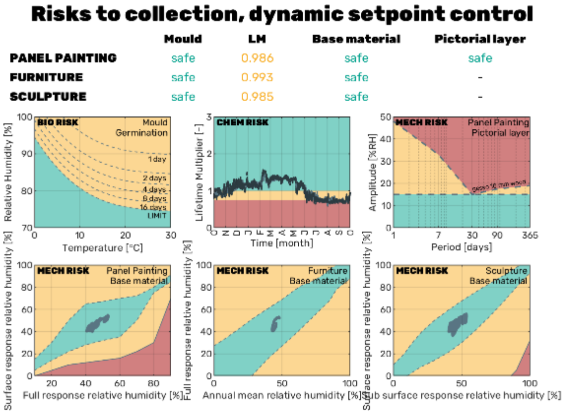
Risks to collection, strict setpoint

	Mould	LM	Base material	Pictorial layer
PANEL PAINTING	safe	0.907	safe	safe
FURNITURE	safe	0.907	safe	-
SCULPTURE	safe	0.907	safe	-

Fig. 6 – Biological, chemical and mechanical risks calculated from measured data for the strict indoor climate in Hermitage Amsterdam.

The difference between figures 6 and 7 is small: the general notion of risks is similar. The dynamic case has a slightly smaller chemical deterioration rate (0.907 versus 0.986, an 8 % longer chemical lifetime for the dynamic case).

The smaller graphs in figures 6 and 7 each represent the behaviour of one of the objects. Figure 8 provides an enlargement for mechanical damage assessment of panel paintings [10].



Risks to collection, dynamic setpoint control

	Mould	LM	Base material	Pictorial layer
PANEL PAINTING	safe	0.986	safe	safe
FURNITURE	safe	0.993	safe	-
SCULPTURE	safe	0.985	safe	-

Fig. 7 – Biological, chemical and mechanical risks calculated from measured data for the dynamically controlled indoor climate in Hermitage Amsterdam.

Vertically the RH experienced by the object's surface is indicated, while horizontally the object's core RH is displayed. The surface has a response time of 4 days, while the core has a response time of 26 days to changes in relative humidity. Because of the difference in response time, a gradient within the material occurs over time; this gradient causes tension in and possibly damage to the object. The green area is the safe area, while the red area presents a sudden rupture of the object. The orange area already presents a dangerous situation, causing micro cracks and permanent deformation.

Figure 8 displays the hypothetical situation in which the humidifier malfunctions during a winter week: the relative humidity in the museum drops to a value of about 25% RH, instead of 50% RH in the strict control case (left). It can be seen in the left figure that the surface RH drops, while the full response of the entire object hardly notices this drop at first. This causes the data to go into the orange area of the graph. There is a moderate risk on mechanical damage present during that time. When the humidifier is repaired, a similar jump occurs when the indoor climate goes back to 50% RH: the surface rises fast in RH, while the bulk of the material responds much slower.

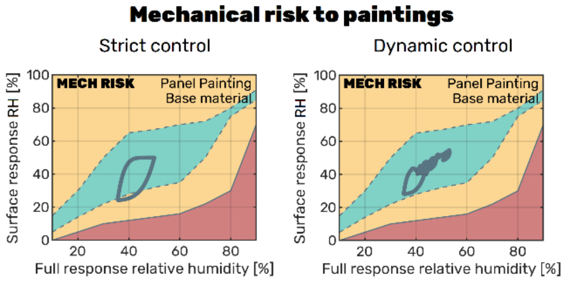


Fig. 8 – Mechanical risk for panel paintings; measured data (grey) fully in green area (right), but also in the orange area during strict control (left)

The right graph of figure 8 shows the exact same situation, but now for the case in which dynamic control is introduced. The data in this graph is not merely a dot at 50% RH, but a 'cloud' of data in between 40% and 55% RH. Because the starting point was not 50% RH, but around 42% RH when the humidifier failed, the drop is much less severe. Moreover, because of a lower indoor temperature, the RH does not drop to 25% RH, but to a mere 30% RH. This results into a significant risk reduction for the panel painting.

4. Discussion & conclusions

Dynamic setpoints are beneficial in multiple ways. A lot of energy can be saved, both in terms of demand delivered by the system and energy consumed by the system. The latter is mainly the focus point of museums, as institutions are interested in cutting operational costs as well as being more sustainable. Moreover, less risk for collections is encountered in case of a system failure, because of the smaller difference between indoor and outdoor conditions. Moreover, visitors perceive much more comfort because their adaptation to the outdoor climate is accounted for.

Existing systems can benefit from adding the DYSECO controller to the building management system. The demand is reduced and less strain is put on the existing systems. Newly designed systems can benefit even further, because they can be designed with a smaller capacity for most of the components, leading to an increase in efficiency during operation.

It is important to note that no changes were made to the systems at all during the measurements, not in terms of software nor in hardware. Only the existing setpoints were taken over and replaced by dynamic setpoints. It is by no means the goal to take over the control or design of HVAC systems, but simply to make the HVAC systems function more according to the needs for collections and thermal comfort, at the lowest energy demand possible.

5. Acknowledgements

The Hermitage Amsterdam museum played a very important role in this project by handing over the controls of their climate systems to researchers. The authors are grateful for their trust and cooperation.

6. References

[1] Brown JP, Rose WB. Humidity and moisture in historic buildings: the origins of building and object conservation. APT Bull. 1996;27:12–24.

[2] Legnér M. On the Early History of Museum Environment Control. Stud. Conserv. [Internet]. 2011;56:125–137.

[3] Michalski S. The Ideal Climate , Risk Management, the ASHRAE Chapter, Proofed Fluctuations, and Toward a Full Risk Analysis Model. Contrib. to Expert. Roundtable Sustain. Clim. Manag. Strateg. Tenerife, Spain: Getty Conservation Institute; 2007. p. 1–19.

[4] ASHRAE. Museums, Galleries, Archives, and Libraries. In: Owen M, editor. Handb. HVAC Appl. SI edition. Atlanta: ASHRAE; 2019. p. 23.1-23.22.

[5] Kramer R, van Schijndel J, Schellen H. Dynamic setpoint control for museum indoor climate conditioning integrating collection and comfort requirements: Development and energy impact for Europe. Build. Environ. [Internet]. 2017;118:14–31. http://dx.doi.org/10.1016/j.buildenv.2017.03.028.

[6] Kramer RP. Clever Climate Control for Culture: Energy efficient indoor climate strategies for museums respecting collection preservation and thermal comfort of visitors. Eindhoven University of Technology; 2017.

[7] Kramer RP, Schellen HL, Schijndel AWM Van. Impact of ASHRAE ' s museum climate classes on energy consumption and indoor climate fluctuations : Full-scale measurements in museum Hermitage Amsterdam. Energy Build. [Internet]. 2016;130:286–294. http://dx.doi.org/10.1016/j.enbuild.2016.08.016.

[8] Kramer R, Schellen L, Schellen H. Adaptive temperature limits for air-conditioned museums in temperate climates. Build. Res. Inf. 2018;46:686–697.

[9] Martens MHJ. Climate Risk Assessment In Museums: degradation risks determined from temperature and relative humidity data. Eindhoven University of Technology; 2012.

[10] Erhardt D, Mecklenburg M. Relative humidity re-examined. Prev. Conserv. Pract. London: The international institute for conservation of historic and artistic works; 1994.

The datasets generated during and/or analysed during the current study are not publicly available because of privacy reasons for the museum involved but are/will be available after contacting the author and with written permission of the museum.