Dynamic setpoint control for museum indoor climate conditioning integrating collection and comfort requirements: Development and energy impact for Europe.

Citation for published version (APA):
Kramer, R. P., van Schijndel, A. W. M., & Schellen, H. L. (2017). Dynamic setpoint control for museum indoor climate conditioning integrating collection and comfort requirements: Development and energy impact for Europe. Building and Environment, 118, 14-31. https://doi.org/10.1016/j.buildenv.2017.03.028

Document license:
CC BY

DOI:
10.1016/j.buildenv.2017.03.028

Document status and date:
Published: 01/06/2017

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.

Download date: 11. Sep. 2020
Dynamic setpoint control for museum indoor climate conditioning integrating collection and comfort requirements: Development and energy impact for Europe

Rick Kramer, MSc *, Jos van Schijndel, PhD, Henk Schellen, PhD
Eindhoven University of Technology, The Netherlands

Article history:
Received 21 October 2016
Received in revised form 17 March 2017
Accepted 18 March 2017
Available online 21 March 2017

Keywords:
Energy
Simulation
Museum
ASHRAE
Thermal comfort

Abstract
This study presents a seven-step algorithm for hourly setpoint calculation of museums' indoor temperature ($T_i$) and relative humidity ($RH_i$) integrating collection requirements (ASHRAE) and thermal comfort requirements. Moreover, building energy simulation results provide insight into the energy impact of five levels of museum indoor climate conditioning applied to four building quality levels (ranging from a historical building to a purpose-built museum building) using weather data from twenty locations throughout Europe. The five levels of indoor climate conditioning were calculated using the presented setpoint algorithm, a validated simulation model of museum Hermitage Amsterdam was adjusted to represent the four building quality levels, and technical-reference-year (TRY) weather data of twenty locations were used. The conclusions: The setpoint algorithm enables smooth control of seasonal adjustments, integrated with permissible short fluctuations of $T$ and $RH$ (according to ASHRAE classes); improving the building quality quickly follows the law of diminishing returns; supposing to result in the same collection risk, subclass Aα (no seasonal adjustments, but larger hourly fluctuations) is more energy efficient than subclass Aσ (with seasonal adjustments, but smaller hourly fluctuations) for most locations; although class AA is more stringent than subclass Aα, class AA appears to require less energy than subclass Aα for some locations, due to efficiency differences of the humidification and dehumidification processes.

© 2017 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

1. Introduction

The indoor climate conditions of museums should serve two purposes: To provide adequate conditions to preserve the artifacts [1]; to provide thermal comfort to visitors and staff. In the case of historical buildings with high cultural significance, the indoor environment may also be important to preserve the interior and building structure itself [2]. Hence, the indoor climate is important for preventive conservation in a wide range of building types, varying from an uninsulated historical building, i.e. buildings with a low quality of the envelope (QoE), to a highly insulated purpose-built museum building, i.e. buildings with a high QoE.

Appropriate indoor environmental conditions for museums, related to a number of building types, are described in indoor climate guidelines. For example, ASHRAE presents indoor climate classes for Museums, Galleries, Archives, and Libraries [3]. These classes include specifications for short-term fluctuations, seasonal adjustments, and permissible levels of both indoor temperature ($T$) and relative humidity ($RH$). The climate classes, which are based on a vast amount of practical and theoretical knowledge [4], range from class AA (precision control) to class D (limited control).

The specifications were not intended to be prescriptive and the various climate classes provide enough opportunities to find climate specifications suitable for many specific museums. However, the notion of an optimal museum environment evolved in the 20th century to ‘the more stable, the better’ [5]. As a consequence, many museums chose the most stringent indoor climate class, like ASHRAE Class AA, supposing this to be the optimum overall solution. However, besides other undesired consequences, conditioning the indoor climate of museums very stringently results in excessive energy consumption.

At the beginning of the 21st century, energy efficiency had become an increasingly important issue for museums, storage rooms, libraries and historical buildings as energy bills kept...
increasing and sustainability had become an important topic. Beginning the discussion in the 1990s [6,7], in recent years, the conservation community is progressively reconsidering the stringent temperature and relative humidity requirements: The way of thinking is changing from pursuing the ideal indoor climate, i.e. preferably no fluctuations in T and RH, to pursuing an appropriate indoor climate, i.e. allowing controlled fluctuations in order to balance collection needs, historic building needs, and energy consumption [8]. If the indoor T and RH ranges may be increased with respect to collection preservation, thermal comfort requirements become more important to determine T setpoints during opening hours [9].

Many studies have focused on the museum environment addressing viable directions for energy efficiency such as system efficiency (e.g. Refs. [10–15]), balancing passive and active climate control (e.g. Refs. [16–19]), controlling solar irradiance (e.g. Ref. [20]), and combinations of measures (e.g. Refs. [21,22]). Whereas many studies focus on realizing the ideal museum climate in an energy efficient way, few studies start from the perspective of an appropriate climate focusing on T and RH ranges to balance the conservation needs and energy consumption, e.g. Refs. [9,14,23–25]. Besides, the multi-objective nature of the museum environment, i.e. collection preservation and thermal comfort of visitors, is addressed by several studies proposing multi-objective assessment methods, e.g. Refs. [24,26–28]. However, a sophisticated algorithm for dynamic setpoint calculation of T and RH integrating the state-of-the-art collection requirements and thermal comfort requirements is still lacking. Three potential problems follow from current T and RH control: (i) Thermal comfort and collection preservation requirements are often combined with a strong focus on the latter compromising thermal comfort; (ii) the setpoints are mostly static values which are implemented manually in the building management system impeding smooth automated adjustments over the seasons potentially endangering the collection; (iii) Energy efficiency is non-optimal due to ineffective use of the permissible T and RH ranges.

This study presents a setpoint calculation algorithm that integrates collection requirements, according to ASHRAE’s museum climate classes, and thermal comfort requirements according to the adaptive comfort approach. The algorithm calculates setpoints for T and RH on an hourly basis using a seven-step process. Moreover, the energy impact of five climate classes, which were calculated using the setpoint algorithm, is explored for four different building types and twenty locations in Europe. A detailed dynamic simulation model has been used of museum Hermitage Amsterdam, including the building, air handling unit (AHU), control systems, and visitors’ heat and moisture gains, see Ref. [29] for information on development and validation. Then, the building model was adjusted to represent museums housed in four different building quality levels, ranging from a historical building (QoE 1) to a purpose-built museum building (QoE 4). Using these four building models, building energy simulations have been performed using weather data from twenty locations in Europe. For each variant, five levels of museum climate control have been simulated: The reference strategy (REF) comprising 21 °C and 50% RH without permissible fluctuations, and four levels of climate control, which have been calculated using the setpoint algorithm, integrating thermal comfort requirements and collection requirements derived from ASHRAE classes AA, Aa, Aα, and B. The thermal comfort requirements follow from a comprehensive year-long survey study in museum Hermitage Amsterdam [30].

The case study museum building, Hermitage Amsterdam, is described in Section 2, Section 3 presents the methodology used for data acquisition and modeling, Section 4 presents the results, and Section 5 provides a discussion and conclusions.

### 2. Museum Hermitage Amsterdam

The current study builds upon previous studies [29–31] that are based on a case study museum: ‘Hermitage Amsterdam’. Therefore, some background information is provided on that museum.

Museum Hermitage Amsterdam is a sister of the State Hermitage Museum in St. Petersburg, Russia, and is located in Amsterdam, the Netherlands. Museum Hermitage Amsterdam has no own collection, but displays loan exhibitions: The artworks mainly belong to the State Hermitage Museum, but also to other museums. The museum is opened seven days per week from 10 h until 17 h and has been welcoming, depending on the exhibition, 7000 to 11,000 visitors per week. Aiming for a very stable museum environment, the employed indoor climate specifications were 21 °C.
and 50% RH without permissible fluctuations.

2.1. The building

The museum is housed in a late 17th-century building and in the past centuries, the building has been changed frequently. The most recent renovation dates from the years 2007–2009 when the building was transformed into a state-of-the-art museum building (see Fig. 1). Only the historical building facade was conserved. The building envelope was newly built inwards, including a cavity and insulation (total thermal resistance 3.7 m²K/W), particularly focusing on airtightness (infiltration rate < 0.1 h⁻¹). Glazing has been replaced by double glazing with reflective coatings (U-value 1.8 W/m²K). Floor heating was applied in the non-exhibition areas and all-air systems were installed to condition the exhibition areas.

Fig. 1a shows the layout of the building. The building has a symmetrical floorplan: Two nearly identical exhibition wings may be recognized by the glass roof on the left and right side in Fig. 1a. This study focuses on one of the two wings: De Keizersvleugel (EN: The Emperor’s Wing). The exhibition areas consist of the main hall (Fig. 1b) and adjacent cabinets (Fig. 1d). Visitors enter the exhibition areas via stairs (Fig. 1c). The ceiling of the main exhibition hall partly consists of a large glass roof with interior sun blinds that are closed almost permanently.

2.2. Internal heat and moisture gains

The visitors’ impact on temperature and humidity consisted of three factors: Heat production, moisture production, and outdoor air supply by a CO₂ controlled ventilation system. Besides, the lighting systems influenced the indoor climate by emitting heat via convection and radiation. All lighting systems included halogen lamps at the time of measurements.

2.3. AHU

In each wing, three AHUs are used to condition the three zones separately: the main exhibition hall in the middle, the cabinets on the left side, and the cabinets on the right side in Fig. 1d. Hence, each zone’s T and RH may be conditioned precisely. The AHUs’ setup is identical, but the flow rates differ, see Fig. 2 for an overview of the setup. From left to right the AHUs consist of a mixing section (outdoor air mixed with recirculation air), dust filter, cooling coil, electric steam humidifier, dehumidification coil with bypass, fan, heating coil, and a filter section (electrostatic, chemical-active carbon and end filter).

Most of the time all air is being recirculated. The outdoor air valves control the supply of fresh outdoor air when the CO₂ levels in the exhibition rooms exceed a threshold value of 1000 ppm. Usually, fresh outdoor air is supplied between 14 h and 17 h.

3. Methodology

Section 3.1 describes the data acquisition. Section 3.2 elaborates on the modeling of the building types, AHU, and visitors’ impact. Section 3.3 presents the collection requirements according to ASHRAE and Section 3.4 presents the used thermal comfort requirements for museum visitors. Section 3.5 explains the developed setpoint algorithm integrating collection and comfort requirements. Section 3.6 explains the acquisition of weather data used for the building energy simulations.

3.1. Data acquisition

For an extensive description of data acquisition see Ref. [29]. Here, only a brief description follows. Outdoor T and RH were measured at the museum site in Amsterdam and logged by the building management system (BMS). Indoor T and RH measurements were retrieved from the museum’s BMS. Four sensors were available in the exhibition room of interest. Outdoor and indoor climate data were logged at a sampling rate of 16 min. Besides, measurement setups were installed on the exhibition room's AHUs logging at a sampling rate of 30 s, see Fig. 2.

The energy consumptions of heating, cooling, and dehumidification were calculated based on the energy exchange between the water side and air side of the coils according to,

![Fig. 1. Aerial view of museum Hermitage Amsterdam. b) One of two main exhibition rooms with a large glass roof. c) The entrance stair from the lobby to the main exhibition room with an air curtain to reduce air exchange. d) A cross section of one side of the building showing the main exhibition room and adjacent cabinets. Source: [29].](image-url)
level scale has been derived from Ref. [34] and their impact on the insulation value and air tightness. The four-building (QoE 4). See Table 1 for an overview of the modifications.

state-of-the-art envelope that is typical for a modern museum housed in a historical building (QoE 1) to a building models with varying QoE ranging from an envelope that is particularly powerful for including control systems.

Extending the model and coupling with other models. The latter is MATLAB and can easily be implemented in Simulink helping in which is indispensable for museum studies; it is programmed in MATLAB Simulink, see Section 3.2.3. HAMBASE was used for the building model was coupled with dynamic models of the AHU in heating, cooling, humidifying and dehumidifying of a multi-zone building. See Refs. [32,33] for extensive information on HAMBASE. Validation exercises of the thermal and hygric part are provided by Ref. [9]. The model of the museum consists of nine zones: One main exhibition hall and all adjacent rooms. The validation of the museum model is comprehensively described in Ref. [9]. The building model was coupled with dynamic models of the AHU in MATLAB Simulink, see Section 3.2.3, HAMBASE was used for the following reasons: Validation studies have shown the model to be capable of accurately simulating both thermal and hygric processes, which is indispensable for museum studies; it is programmed in MATLAB and can easily be implemented in Simulink helping in extending the model and coupling with other models. The latter is particularly powerful for including control systems.

3.2.2. Four QoE-variants

The validated building model has been transformed into four building models with varying QoE ranging from an envelope that is typical for a museum housed in a historical building (QoE 1) to a state-of-the-art envelope that is typical for a modern museum building (QoE 4). See Table 1 for an overview of the modifications and their impact on the insulation value and air tightness. The four-level scale has been derived from Ref. [34]:

QoE 1 An original historical building envelope. The envelope consists of an original stone or brick construction having a thickness of about 400 mm without insulation. Windows are simple and consist of wooden window frames with single glazing.

QoE 2 A slightly modified historical building envelope. The window frames have been modified or replaced containing double glazing or an additional sheet of glazing has been added either on the inside or the outside of the original window frame. The amount of air leakage has been reduced, especially around window frames.

QoE 3 A completely modified building envelope. Changes are not limited to windows only as the entire wall has been modified. The air tightness and thermal resistance have been increased by adding insulation. Window frames have been modified and glazing has been replaced by modern low-emission glazing.

QoE 4 A purpose-built modern museum envelope. The envelope includes a cavity with insulation and air tightness is improved by using foils. Also, window frames are airtight.

3.2.3. AHU

The following AHU-components were modeled in detail using MATLAB Simulink: the high-temperature cooling coil (HT-CC) used for sensible cooling, the low temperature cooling coil (LT-CC) used for dehumidification, the low-temperature heating coil (LT-HC), and the steam humidifier. Moreover, a constant power consumption was used to model the fan as the fan operated at a constant rotation speed. Calibration and validation were undertaken within the Simulink environment. The coils were modeled according to ASHRAE RP-1194 [35,36]. For each row, two ODEs were solved: Heat transfer from the water to the coil and heat transfer from the coil to the air. Moreover, two scenarios were modeled: Dry surface condition and wet surface condition. The steam humidifier was modeled using the enthalpy balance of the air flow and steam injection rate. Therefore, both moisture increase and temperature increase of the air were taken into account. The characteristic flow curves of the hydraulic valves controlling the water mass flow rate of the coils and the fresh outdoor air supply were also modeled. The AHU-models’ development, validation, and coupling with the building model are described comprehensively in Ref. [29].

3.2.4. Reducing computational time: linearizing coil models using state space

In total, 400 simulation runs were needed: five setpoint strategies, four QoEs, twenty locations. The expected computational time was a matter of concern since the original model, as presented in Ref. [29], takes 23 h for a single run. To substantially reduce
computational time, the detailed coil models of the heating, cooling, and dehumidification coils were replaced by state space models estimated using the System Identification Toolbox of MATLAB [37]. The computational time of one run was reduced to 2 h, resulting in a total computational time of just over 33 days.

The detailed coil models were used to create input and output data needed for the inverse modeling of the state space models. The System Identification Toolbox was used with the following settings: discrete-time with a sample time of 10 s, the estimation method was N4SID, the focus was set to ‘simulation’. The state space models were implemented in Simulink using the Idmodel-block.

The dehumidification coil was modeled using two state space models: dry and wet conditions. If the resulting air temperature was lower than the dew point temperature, the simulation result of the state space model LT-CCdry was used, otherwise the simulation result of the state space model LT-CCwet was used.

Table 2 shows the models’ number of states, the inputs, and the simulation performance. The models HT-CC, LT-CCdry, and LT-HC required four states; the inputs consist of incoming air temperature (T_a,i) and thermal power transferred from the water side to the air side (P_w); the outputs only consist of air temperature (T_a,o) according to, on output y’ is not correctly described by the model.

A model was considered suitable and valid if the autocorrelation of the residuals and the cross correlations between the residuals and inputs were within the 95% confidence limits, a step response resulted in a stable output, and the goodness of fit could not significantly be improved by increasing the number of states. Fig. 3 shows the validation of the HT-CC state space model and its input signals. A chirp signal was used for the inputs T_a,i and P_w covering a range of frequencies. The other state space models perform very similarly.

3.2.5. Visitors impact

Indoor CO₂ data have been analyzed, using the decay curve method, to derive an hourly visitors profile for each day of the week. Based on the number of visitors, the internal heat gains, moisture gains, and CO₂ production by visitors are calculated for each hour. Moreover, the heat and moisture gains are dependent on the indoor temperature. The simulated CO₂ level is used for CO₂ controlled ventilation (active above 1000 ppm). For more information on the development, validation, and implementation, see Ref. [29].

3.3. Collection requirements: ASHRAE’s museum climate classes

ASHRAE’s indoor climate guidelines for museums, galleries, archives, and libraries include specifications for permissible short-term fluctuations, seasonal adjustments, and recommended levels for indoor T and RH. These specifications are shown in table 3 in Ref. [3]: Four classes are defined, along with associated collection risks: AA (no risk to most objects), A (small risk to highly vulnerable objects, no risk to most objects), B (moderate risk to highly vulnerable objects, small risk to most objects), C (prevent high risk extremes), D (prevent dampness). Class A is divided into subclass A_A, with seasonal adjustments and limited daily fluctuations, and subclass A_B, which allows larger daily fluctuations, but no seasonal adjustments. Classes C and D are not applicable for most museums. Therefore, this study only considers classes AA, A_A, A_B, and B. Table 3 shows T and RH specifications for these classes. Note that, according to ASHRAE, the starting point for setpoint calculation may be the historical annual average that the collection has been exposed to, or 21 °C and 50% RH for loan exhibitions. This study uses the latter.

3.4. Thermal comfort requirements

Besides collection preservation, the indoor climate in museums should provide thermal comfort to visitors and staff. RH is predominantly determined by collection requirements, whereas T is predominantly determined by thermal comfort requirements during opening hours [9]. After all, even class AA allows seasonal T-adjustments of 5 K up and 5 K down resulting in a range of

### Table 1
**Specification of the used QoE levels.**

| QoE  | Exterior wall | Glazing | Infiltration rate [h⁻¹] |
|------|---------------|---------|------------------------|
| 1    | 400 mm brick, plastered | single | 5.7 | 0.01 | 0.8 | 1.0 |
| 2    | 400 mm brick, plastered | double | 3.2 | 0.03 | 0.7 | 0.4 |
| 3    | 400 mm brick, 100 mm insulation, plastered | double, low-emission | 1.4 | 0.03 | 0.7 | 0.2 |
| 4    | 100 mm brick, cavity, 150 mm insulation, 100 mm brick, plastered | double, low-emission | 1.3 | 0.05 | 0.3 | 0.1 |

### Table 2
**States, inputs, outputs, and performance of the state space models.**

| Model | # states | u | y | Goodness of fit [%] | MSE [°C] |
|-------|----------|---|---|---------------------|---------|
| HT-CC | 4        | [T_a,i, P_w] | T_a,o | 93.15 | 0.027 |
| LT-CCdry | 4     | [T_a,i, P_w] | T_a,o | 93.79 | 0.088 |
| LT-CCwet | 6     | [H_u, P_w] | [H_a,i, T_a,i] | 95.32/94.31 | 0.278² |
| LT-HC | 4        | [T_a,i, P_w] | T_a,o | 98.60 | 0.012 |

² Combined MSE of H_a,i and T_a,o.
16 °C–26 °C for loan exhibitions.

Most research on human thermal comfort relates to office environments. Knowledge on thermal comfort in the museum environment is scarce. Therefore, a comprehensive study was undertaken in museum Hermitage Amsterdam during the year 2015 to assess the thermal comfort of museum visitors under different indoor climate conditions and varying outdoor climate conditions. The study comprised subjective surveys (n = 1248),...
to indoor climate measurements, and outdoor climate measurements. We refer to [30] for more information on this study. The work enabled the development of Adaptive Temperature Limits (ATL) validated for a museum environment. The upper temperature limit is calculated according to,

$$T_{\text{upper limit}} = 20.7 + 0.175 \, T_{\text{e.ref}}$$

and the lower temperature limit is calculated according to,

$$T_{\text{lower limit}} = 18.3 + 0.175 \, T_{\text{e.ref}}$$

where the reference outdoor temperature $T_{\text{e.ref}}$ is calculated according to,

$$T_{\text{e.ref}} = \frac{T_{\text{e,i}} + 0.8T_{\text{e,i-1}} + 0.4T_{\text{e,i-2}} + 0.2T_{\text{e,i-3}}}{2.4} \quad (6)$$

in which $T_{\text{e,i}}$ is the average outdoor temperature of the survey day, $T_{\text{e,i-1}}$ the average of the day before, etc. The average is the arithmetic mean of the minimum and maximum outdoor temperature of the given day. This reference outdoor temperature has been proposed by van der Linden et al. [38] and is an implementation of the exponentially weighted running mean outdoor temperature by Nicol [39].

Fig. 4 shows the ATL used to calculate the upper limit for $T_i$ (cooling setpoint) and the lower limit for $T_f$ (heating setpoint). The temperature range between the limits is 2.4 °C and is considered to represent the 90% acceptance class, i.e. the upper limit represents a mean thermal sensation vote of +0.5 and the lower limit represents a mean thermal sensation vote of −0.5. The limits have been validated on the range 5 °C < $T_{\text{e.ref}}$ < 25 °C, but these limits were extrapolated in this study.

The ATL implicitly takes into account the phenomena of adaptation and expectation which might be different from office environments. Moreover, the metabolic rate (heat production) of museum visitors is slightly higher than that of office workers. Hence, the resulting temperature bandwidth differs from the ATL for office environments.

There are two main reasons why the adaptive concept was employed: 1) Analysis of the museum visitors’ thermal sensation votes revealed that there was a strong correlation between the comfort temperature range and the running mean outdoor temperature, and hence, the adaptive concept was applicable; 2) Using the adaptive concept enables the easy calculation of the permissible upper and lower temperature limit, and consequently, the temperature limits following from thermal comfort requirements may easily be integrated with temperature limits following from collection preservation requirements. The potential of integration is very important for the calculation of the setpoints for temperature, see Fig. 6.

3.5. Setpoint algorithm combining comfort and collection requirements

A setpoint algorithm has been developed to calculate the setpoints for heating, cooling, humidification, and dehumidification, which integrates thermal comfort requirements for visitors (Section 3.4) and collection requirements according to the ASHRAE classes (Section 3.3). Fig. 5 shows the workflow consisting of seven steps.

Steps 3 and 5 are used to calculate the setpoints based on collection requirements for $T$ and $RH$, respectively. These steps require a translation from the information provided in Table 3 into an algorithm. Table 3 is based on a concept differentiating between short and seasonal fluctuations. The latter is realized by adjustments in the system setpoint (21 °C and 50% RH for loan exhibitions). To ensure a smooth course of $T$ and $RH$, this study proposes to use a moving seasonal average. The seasonal average is calculated using a simple moving average filter with a centrally positioned averaging window covering three months according to,

$$X_{\text{running},i} = \frac{1}{n} \sum_{a=-n/2}^{i-n/2} X_a \quad (7)$$

where $X_{\text{running}}$ denotes the seasonal running average, $n$ is the number of data points in one season ($n = 2190$ in the case of hourly values), $i$ is the current data point in the data range, and $a$ is the point in the seasonal period (averaging window). Subsequently, the system setpoint is limited by the maximum seasonal adjustments as provided in Table 3. Section 4.1 elaborates on the results of the proposed workflow.

3.6. BES weather data acquisition

Outdoor climate files of twenty locations in Europe have been acquired from EnergyPlus® Weather Database [40]. The climate files were converted to the climate file format required for HAMBASE. The following variables were used from the climate files: diffuse solar radiation on the horizontal plane [W/m²], extraterrestrial dry bulb temperature [0.1 °C], direct normal solar radiation [W/m²], wind speed [m/s], wind direction [°], relative humidity [%], time of rainfall [0.1 h], sum of rainfall [0.1 mm], cloud cover [0–8]. The weather data files comprise typical climate years for energy calculations, mostly IWEC, but also SWEC (Spain), INETI (Portugal), and IGDG (Italy). These years have been assembled from multiple years to adequately represent the long-term weather conditions of a particular location.

4. Results

4.1. Setpoint algorithm integrating comfort and collection requirements

Fig. 5 summarizes the underlying methodology used to integrate collection requirements and thermal comfort requirements to calculate setpoints for heating, cooling, humidification, and dehumidification. Fig. 6 shows the results of this methodology for the following variant: location Amsterdam, building type QoE 2, and collection requirements according to ASHRAE climate subclass $A_2$. 

![Fig. 4. ATL according to a 90% acceptance level [30].](image-url)
illustrate the effect of controlled seasonal adjustments.

Step 1. Calculate $$T_{\text{set,comf}}$$
- Calculate $$T_{\text{set,comf}}$$ according to comfort requirements
- Equations (4-6)

Step 2. Simulate $$T_i$$
- Apply $$T_{\text{set,comf}}$$
- Simulate $$T_i$$

Step 3. Calculate $$T_{\text{set,cool}}$$
- Calculate seasonal average of $$T_i$$
- Apply limits to seasonal average
- Superpose allowed short fluctuations

Step 4. Choose $$T_{\text{set}}$$
- a) determine most stringent $$T_{\text{set}}$$: step 1 or step 3.
- b) Opening hours: most stringent $$T_{\text{set}}$$
  Closing hours: apply $$T_{\text{set,cool}}$$

Step 5. Simulate $$T_i$$ & $$RH_i$$
- Simulate $$T_i$$ with new $$T_{\text{set}}$$
- $$RH_i$$ free floating

Step 6. Calculate $$RH_{\text{set}}$$
- Calculate seasonal average of $$RH_i$$
- Apply limits to seasonal average
- Apply limits to short-term fluctuations

Step 7. Simulate
- Simulation with $$T_{\text{set}}$$
- and $$RH_{\text{set}}$$

integrated with comfort requirements. Subclass $$A_s$$ was chosen to illustrate the effect of controlled seasonal adjustments.

Step 1. the lower and upper limits of temperature are calculated according to the thermal comfort requirements. The equations involve a moving average including the current day and preceding three days, hence, the limits may vary substantially over a period of a couple of weeks.

Step 2. shows the simulated indoor temperature ($$T_i$$): the lower limit is used as the heating setpoint and the upper limit is used as the cooling setpoint. $$T_i$$ remains close to the lower limit in winter, increases in spring, and covers frequently the entire range in summer, approaching the lower limit mostly at night and approaching the upper limit mostly during the day.

Step 3. the simulated $$T_i$$ is used to calculate the system setpoint including seasonal adjustments. Since the setpoints are calculated for loan exhibitions, not the annual average, but 21 °C is used as reference setpoint (see Table 3). Subclass $$A_s$$ allows seasonal adjustments of $$-10 \text{ °C}$$ and $$+5 \text{ °C}$$ resulting in a permissible range of 11–26 °C. Therefore, the resulting system setpoint in Step 3 is equal to the seasonal average and is not limited. The short fluctuation limits are superposed resulting in the collection requirements for $$T_i$$.

Step 4. a: the limits according to Step 1 (comfort) and Step 3 (collection) are compared for each hourly value, choosing the most stringent limit. This step ensures that both thermal comfort and thermal collection requirements are met. Step 4b: the limits found in Step 4a are applied from 9 h to 17 h to provide thermal comfort during the opening hours (10–17 h); the limits found in Step 3 are applied during the remaining hours requiring only collection preservation.

Step 5. $$T_i$$ is simulated using these final limits and $$RH_i$$ is simulated as free floating. Notice how $$T_i$$ decreases at night and starts increasing as the lighting systems are turned on at 7 h and increases more when visitors arrive starting at 10 h.

Step 6. the simulated $$RH_i$$ is used to calculate the system setpoint including seasonal adjustments. As the setpoints are calculated for loan exhibitions, not the annual average, but 50% RH is used as reference setpoint (see Table 3). Besides, subclass $$A_s$$ allows seasonal adjustments of ±10% RH. Therefore, the seasonal moving average is calculated of $$RH_i$$ and then limited to 40–60% RH. Then, the short fluctuation

limits are superposed resulting in the collection requirements for $$RH$$.

Step 7. the final limits of subclass $$A_s$$ are applied and the indoor climate is simulated.

4.2. Comparison to experimental results

Fig. 7 shows the energy consumption of strategies REF, class AA, and subclass $$A_d$$ applied to museum Hermitage Amsterdam. Fig. 7a shows experimental results of a study conducted by Kramer et al. [41] in which the energy consumption was measured in detail at component level in the AHU. Fig. 7b shows the energy consumptions as simulated by the model presented in this study. The absolute energy consumptions for heating, cooling, and dehumidification show some differences which may be attributed predominantly to the following. The experimental study (Fig. 7a) was conducted from April 2015 to March 2016, whereas the simulation model was validated using measurements from June 2014 to June 2015 and the results in Fig. 7b follow from a simulation using IWE weather data. Therefore, there are two major reasons for the differences: (i) the two results are based on different internal loads by visitors as measurements were conducted during different exhibitions; (ii) the results are based on different prevailing outdoor climate conditions. However, the relative savings of the ASHRAE classes AA and $$A_d$$ appear to be close. So, although the internal loads and external loads were different, the relative savings differ only 4% for class AA and 1% for subclass $$A_d$$. This conclusion contributes to the confidence that the simulation results of the other locations are relevant.

4.3. Detailed analysis of location Amsterdam

Fig. 8 provides a detailed overview of energy consumptions for location Amsterdam. The influence of the QoE on the energy consumption is significant, although the results also clearly show that the law of diminishing returns applies: Only a marginal energy reduction will be achieved by improving from QoE 3 to QoE 4 because the decreased heating demand is counteracted by the increased cooling demand. Moreover, QoE 1 predominantly requires heating, whereas QoEs 3 and 4 require almost no heating for classes AA to B.

Fan energy becomes increasingly important for QoE 3 and QoE 4, particularly for the less stringent indoor climate strategies ($$A_s$$, $$A_d$$,
and B): fan energy makes up to 50% of the total energy consumption.

Subclasses Aₙ and Aₐ share the same collection risk profile, see Table 3. However, from an energy saving perspective, subclass Aₐ appears to be more economical than subclass Aₙ (up to 20% more economical for QoE 2).

Fig. 9 shows $T_i$ (left) and $RH_i$ (right) according to ASHRAE classes AA, Aₙ, Aₐ, and B for QoE 1. Seasonal variations occur in all classes for $T_i$, but are only allowed in classes Aₙ and B for $RH_i$. Fig. 10 shows the results for QoE 4. Comparing the indoor climates of QoE 1 and QoE 4 shows clearly a reduction of short-term fluctuations. Incidentally, the lower and upper limits are exceeded, mostly in QoE 1.
This is the result of the system and building dynamics that are realistically reproduced by the simulation model.

For QoE 4, $T_i$ remains predominantly close to the upper limit because of the higher insulation level combined with the high internal heat gains of visitors and lighting systems. Although short-term fluctuations of $RH_i$ are limited, the permissible seasonal fluctuations are effectively utilized as $RH_i$ remains close to the lower limits in winter and increases towards summer. $T_i$ of class B illustrates the significant impact of the thermal comfort requirements: although class B implies a rather wide range of permissible temperatures, the more stringent comfort requirements in combination with the slow dynamics of the building result in a rather narrow range of $T_i$. So, the permissible fluctuation range from a collection preservation perspective is not fully

---

**Fig. 7.** Energy consumption of strategies REF, class AA, and subclass $A_d$: a) Measured by Kramer et al. [31] from June 2014 to June 2015 in museum Hermitage Amsterdam. b) Simulated using the model presented in this study with IWEC weather data.

**Fig. 8.** Location Amsterdam, The Netherlands: Annual energy consumption specified for QoE 1 to 4 and relative energy savings of ASHRAE’s climate classes.
utilized. In contradiction, QoE 1 shows an effective use of the night setback.

4.4. Locations

Building energy simulations have been performed using weather data of the locations shown in Fig. 11, ranging from Northern Sweden to Southern Italy and from Ireland to Turkey. For every location, twenty building simulations have been performed: five setpoint strategies have been simulated for building envelopes QoE 1 to QoE 4. In total 400 simulations have been performed.

Table 4 presents the results for the locations and QoEs: Total annual energy consumptions are provided for strategies REF and savings relative to REF are provided for strategies AA, As, A4, and B. Köppen-Geiger outdoor climate classes are included to provide some guidance on the typical outdoor climate for each location, which are explained in Table 5 [42]. For ease of comparison, a graphical representation of the specific energy consumptions (heating, cooling, dehumidification, and humidification) is provided in the appendix.

The law of diminishing returns does apply to the QoE: locations Stockholm, Bergen, and Madrid even show a higher REF energy consumption for QoE 4 than for QoE 3. Moreover, many locations show equal or very close energy consumptions for QoE 3 and QoE 4.

From the perspective of energy consumption, it was shown for location Amsterdam that subclass A4 is to be preferred over subclass A3. However, Table 4 reveals that this is not generally true and that the outcome heavily depends on the location, i.e. the outdoor climate. Subclass A4 is more economical than subclass A3 for locations 13 (Venice) and 17 (Rome). The energy consumption of both subclasses is nearly equal for locations 12 (Belgrade) and 16 (Lisbon). For locations 15 (Madrid), 18 (Palermo), and 20 (Istanbul) the preferred subclass depends on the QoE. For the other 13 locations, subclass A4 is significantly more economical than subclass A3.

Table 3 and Fig. A1 also show that for some locations, most unexpectedly, class AA appears to be more economical than subclass A3, although subclass A3 imposes less stringent limits on RHi. Class AA requires significantly less energy than subclass A3 for the
locations 1 (Kiruna), 2 (Stockholm), 3 (Bergen), 4 (Copenhagen), 5 (Dublin), 6 (London), and 8 (Berlin). Fig. 12 provides a closer look at $R_{hi}$ of a QoE 2-building in Stockholm according to classes AA and A_s. Subclass A_s allows a lower $R_{hi}$ in winter than class AA. Because seasonal adjustments are limited, $R_{hi}$ of subclass A_s only reaches the upper limit of 55% RH in summer for a short time span. Although subclass A_s saves many hours of humidification in winter, it requires more hours of dehumidification in summer than class AA. Since dehumidification was realized by deep-cooling and reheating, dehumidification requires much energy. Hence, compared to class AA, subclass A_s dehumidification energy increased more than humidification energy could be conserved.

5. Discussion and conclusions

The focus of this study is on efficient setpoint strategies for $T$ and $R_{hi}$ control, not on efficient HVAC systems. Efficient setpoint strategies are the first step in reducing museums’ energy demand. Previously, a detailed simulation model had been developed of Museum Hermitage Amsterdam which was validated comprehensively to calculate the annual energy consumption [29]. In the current study, the model’s exterior walls, glazing, and infiltration rate have been varied to obtain four different QoEs, representing museums housed in historical buildings (QoE 1) up to museums housed in purpose-built museum buildings (QoE 4). These four building models have been simulated using weather data of twenty locations throughout Europe and five different setpoint strategies for the indoor climate (an ultra-stable reference strategy REF, and ASHRAE classes AA, A_s, A_g, and B, combined with thermal comfort requirements) resulting in a total of 400 simulations.

The developed setpoint algorithm uses a simple moving average filter to calculate the seasonal average of $R_{hi}$ and $T_i$. It is an unweighted mean taken from an equal number of data points on either side of a central value ($-0.5$ window $< x < +0.5$ window) ensuring that variations in the mean are aligned with variations in the data rather than being shifted. Two issues arise from this approach. Firstly, all $R_{hi}$ or $T$ values within the averaging window are equally weighted, whereas the values just outside the window

Fig. 10. Location Amsterdam, The Netherlands, QoE 4: calculated setpoints (blue curves) and resulting indoor climate (gray curves) according to ASHRAE’s climate classes combined with comfort requirements (only during opening hours). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
are not taken into account at all. The necessity of this approach may be questioned as the artifacts’ perception of indoor climate variations gradually fades over time. So, a weighted moving average filter seems more logical. However, more research is needed to develop such a filter. Secondly, artifacts don’t perceive future climate variations. So the validity of applying a centrally positioned averaging window is under question. However, the reason to apply a centrally positioned window is to keep the running mean aligned with the indoor climate variations. More research is needed to develop a moving average filter that takes into account past values only, yet limiting the misalignment. Moreover, this is also needed to enable implementation of such a setpoint algorithm in a museum as future values are unknown.

Mostly, museums have high internal heat gains from visitors and lighting systems. Therefore, the law of diminishing returns applies.

**Table 4**

| Köppen class | QoE 1 | QoE 2 | QoE 3 | QoE 4 |
|--------------|------|------|------|------|
| Kiruna       | Dfc  | 2870 | 27   | 20   | 28   |
| Stockholm    | Dfb  | 2500 | 37   | 32   | 46   |
| Bergen       | Cfb  | 2180 | 36   | 26   | 45   |
| Dublin       | Cfb  | 2340 | 42   | 39   | 51   |
| London       | Cfb  | 2390 | 44   | 38   | 57   |
| Amsterdam    | Cfb  | 2910 | 42   | 47   | 55   |
| Berlin       | Dfb  | 2330 | 43   | 35   | 52   |
| Kiev         | Dfb  | 2870 | 40   | 42   | 50   |
| Munich       | Cfb  | 2550 | 39   | 39   | 48   |
| Paris        | Cfb  | 2710 | 44   | 44   | 58   |
| Belgrade     | Dfb  | 3160 | 39   | 53   | 54   |
| Venice       | Cfa  | 3750 | 32   | 51   | 46   |
| Geneva       | Cfb  | 2450 | 44   | 44   | 55   |
| Madrid       | Bsk  | 1300 | 34   | 31   | 39   |
| Lisbon       | Csa  | 3300 | 44   | 67   | 64   |
| Rome         | Csa  | 3510 | 38   | 58   | 56   |
| Palermo      | Csa  | 2740 | 47   | 63   | 65   |
| Athens       | Csa  | 2800 | 46   | 48   | 64   |
| Istanbul     | Cfa  | 3130 | 37   | 51   | 50   |

| Köppen class |
|---------------|
| Dfc arid/steppe/cold |
| Bsk arid/steppe/cold |
| Cfa temperate/without dry season/hot summer |
| Csa temperate/dry summer/hot summer |
| Cfb temperate/without dry season/warm summer |
| Dfb cold continental/without dry season/warm summer |

| Class | Characteristics |
|-------|-----------------|
| Bsk   | arid/steppe/cold |
| Csa   | temperate/dry summer/hot summer |
| Cfa   | temperate/without dry season/hot summer |
| Cfb   | temperate/without dry season/warm summer |
| Dfb   | cold continental/without dry season/warm summer |

**Table 5**

| Class | Characteristics |
|-------|-----------------|
| Bsk   | arid/steppe/cold |
| Cfa   | temperate/without dry season/hot summer |
| Cfb   | temperate/without dry season/warm summer |
| Dfb   | cold continental/without dry season/warm summer |

**Fig. 11.** The locations included in this study.
to improving the QoE: beyond a certain level of QoE, the internal heat gains are higher than the heating demand, hence, the cooling demand will increase. So, a well-balanced QoE is of high importance. Also, it has been shown that improving the QoE reduces short-term fluctuations, e.g. daily fluctuations. So, applying the limits according to subclass $A_0$ to a building with QoE1 results in a different indoor climate than applying these limits to a building with QoE 4. So, the collection is exposed to a different climate, and hence, the degradation risk may differ.

ASHRAE class A is divided into subclasses $A_3$ and $A_4$, both sharing the collection degradation risk associated with class A, see Table 3. Given the significant different indoor climates that may result from these subclasses, it is fair to question the validity of sharing the same risk description.

For some locations, class AA appeared to outperform subclass $A_3$ regarding energy economy. Compared to class AA, subclass $A_3$' humidity energy savings were counteracted by its increased dehumidification energy. Theoretically, subclass $A_3$ should enable lower energy consumptions than class AA as less stringent limits apply. In order to take the effect of air-conditioning processes’ efficiencies into account, future research is needed.

It must be noted that the validity of some of the results is confined to museums employing the same AHU configuration as the case study museum, particularly with respect to the electric steam humidifier and dehumidification by deep-cooling and reheating. For example, the use of a desiccant wheel for dehumidification or ultrasonic humidification may imply different results. Moreover, the case study museum is characterized by several AHUs serving each zone separately for precise $T$ and RH control. Although this is common in many museums, other museums may employ an AHU serving multiple zones via a VAV (Variable Air Volume) ventilation system. However, the aforementioned limitations only apply to conclusion five presented hereafter.

The main conclusions of the study are:

1. A setpoint algorithm has been developed integrating collection requirements according to ASHRAE’s climate classes and thermal comfort requirements. The setpoint algorithm enables smooth control of seasonal adjustments, integrated with permissible short fluctuations of $T$ and RH.
2. For location Amsterdam and QoE 4, the simulated savings have been verified with measurements undertaken in museum Hermitage Amsterdam. Compared to the REF-strategy, the relative savings were 53% (AA), 61% (A$_3$), 64% (A$_4$), and 74% (B).
3. Improving the QoE follows the law of diminishing returns. QoE 4 did not show a substantial energy reduction compared to QoE 3 for all locations. In fact, some locations even showed increased energy consumptions. Hence, a balance between internal heat gains and insulation level is of high importance.
4. Although subclasses $A_3$ and $A_4$ would result in the same collection degradation risk according to ASHRAE, the resulting energy consumptions may differ substantially. Which class is more economical mainly depends on the outdoor climate and, to a lesser extent, the QoE. However, subclass $A_4$ is to be preferred for most museums.
5. For some locations, class AA resulted in a lower energy consumption than subclass $A_4$ due to air-conditioning efficiency differences between humidification and dehumidification. This aspect requires more research.

Acknowledgements

We thank the Building Physics and Services Laboratory of Eindhoven University of Technology and Kuijpers Building Services for their efforts regarding the experimental setup. Moreover, we thank museum Hermitage Amsterdam for their confidence and cooperation. We thank Zeeuws Museum, Strukton Worksphere, Kuijpers Building Services, and Stichting PIT for their financial support.
Appendix
Fig. A1. Annual energy consumption specified for QoE 1 to 4 and relative energy savings of ASHRAE's climate classes.
References

[1] G. Thomson, The Museum Environment, second ed., Butterworth-Heinemann, London, 1986.

[2] B. Ankersmit, Klimaatwerk: Richtlijnen Voor Het Museale Binnenklimaat, Amsterdam University Press, Amsterdam, 2009.

[3] ASHRAE, Museums, libraries and archives, in: M.S. Owen (Ed.), ASHRAE Handb. HVAC Appl. St Edition, ASHRAE, Atlanta, 2011, pp. 23.1–23.23.

[4] S. Michalski, The ideal climate, risk management, the ASHRAE chapter, proofed fluctuations, and toward a full risk analysis model, in: Contrib. To Expert. Roundtable Sustain. Clim. Manag. Strateg., Getty Conservation Insti- tute, Tenerife, Spain, 2007, pp. 1–19.

[5] J.P. Brown, W.B. Rose, Humidity and moisture in historic buildings: the origins of building and object conservation, APT Bull. 27 (1996) 12–24.

[6] J. Ashley-Smith, N. Umney, D. Ford, Let’s be honest: realistic environmental parameters for loaned objects, in: Prev. Conserv. Pract. Theory Res, ICC, Ottawa, 1994.

[7] T. Oresezyn, M. Cassar, K. Fernandez, Comparative study of ariconditioned and non ariconditioned Museums, in: Prev. Conserv. - Pract. Theory Res. Pre- prints IIC Congr., ICOM, Ottawa, 1994.

[8] K. Dardes, S. Staniforth, Preventive conservation: sustainable stewardship of collections, GCI Conserv. Perspect. 30 (2015) 1–13.

[9] R.P. Kramer, M.P.E. Maas, M.H.J. Martens, A.W.M. van Schijndel, H.L. Schellen, Energy study of a medieval store, restored as a museum, Energy Build. 35 (2003) 951–961, http://dx.doi.org/10.1016/S0378-7775(03)00025-2.

[10] F.J. Garcia-Diego, A. Fernandez-Navajas, P. Beltran, P. Merello, Study of the effect of the strategy of heating on the mudejar church of Santa Maria in Ateca (Spain) for preventive conservation of the altarpiece surroundings, Sensors (Basel) 13 (2013) 11407–11423, http://dx.doi.org/10.3390/s130911407.

[11] L. Bella, A. Capozzoli, P. Mazzei, F. Minichielo, A comparison of HVAC systems for artwork conservation, Int. J. Refrig. 30 (2017) 1439–1451, http://dx.doi.org/10.1016/j.ijrefrig.2017.03.005.

[12] F. Ascione, L. Bella, A. Capozzoli, F. Minichielo, Energy saving strategies in air- conditioning for museums, Appl. Therm. Eng. 29 (2009) 676–686, http://dx.doi.org/10.1016/j.applthermaleng.2008.03.040.

[13] M. Papadopoulou, a. Avgelis, M. Santamouris, Energy study of a medieval tower, restored as a museum, Energy Build. 57 (2013) 106–116, http://dx.doi.org/10.1016/j.enbuild.2013.02.015.

[14] H.E. Silva, F.M.A. Henriques, T.A.S. Henriques, G. Coelho, A sequential process to assess and optimize the indoor climate in museums, Build. Environ. 104 (2016) 21–34, http://dx.doi.org/10.1016/j.buildenv.2016.04.023.

[15] R.P. Kramer, L. Schellen, M. Doornbos, H. Schellen, Adaptive Temperature Limits (ATL), from theory to practice, in: M.N. Assimakopoulos, Energy efficiency and thermal comfort in historic buildings: a review, Renew. Sustain Energy Rev. 61 (2016) 70–85, http://dx.doi.org/10.1016/j.rser.2016.03.018.

[16] R.P. Kramer, H.L. Schellen, Schijndel A.W.M. van, Impact of ASHRAE’s museum climate classes on energy consumption and indoor climate fluctuations: full- scale measurements in museum Hermitage Amsterdam, Energy Build. 130 (2016) 286–294, http://dx.doi.org/10.1016/j.enbuild.2016.08.016.

[17] M.H. de Wit, Heat Air and Moisture Model for Building and Systems Evalua- tion, Eindhoven University Press, Bevousteden, Eindhoven, 2006.

[18] A.W.M. van Schijndel, Integrated Heat Air and Moisture Modeling and Simulation, Eindhoven University of Technology, 2007.

[19] M.H.J. Martens, Climate risk assessment, in: Museums: Degradation Risks Determined from Temperature and Relative Humidity Data, Eindhoven Uni- versity of Technology, 2012.

[20] X. Zhou, J. Braun, A simplified dynamic model for chilled-water cooling and dehumidifying Coils Part 1: development (RP-1194), HVAC&R Res. 13 (2007) 785–804, http://dx.doi.org/10.1080/10789690601039586.

[21] X. Zhou, J. Braun, A simplified dynamic model for chilled-water cooling and dehumidifying Coils Part 2: experimental validation (RP-1194), HVAC&R Res. 13 (2007) 805–817, http://dx.doi.org/10.1080/10789690601039587.

[22] R. Kramer et al., Fundamental multi-scale measurements in museum Hermitage Amsterdam, Energy Build. 158 (2015) 446–458, http://dx.doi.org/10.1016/j.apenergy.2015.08.044.

[23] F. Ascione, F. Minichielo, Microclimatic control in the museum environment: air diffusion performance, Int. J. Refrig. 33 (2010) 806–814, http://dx.doi.org/10.1016/j.ijrefrig.2009.12.017.

[24] M.C. Peel, B.L. Finlayson, T.A. McMahon, Updated World map of the Köppen-Geiger climate classification, Hydrol. Earth Syst. Sci. 11 (2007) 1633–1644, http://dx.doi.org/10.1011/0794-2984/2006/0139.