

Intermittent conditioning of library archives

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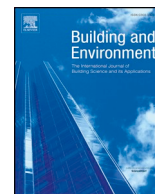
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Intermittent conditioning of library archives: Microclimate analysis and energy impact



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ABSTRACT

Libraries and archives house a majority of cultural heritage objects. The main purpose of libraries and archives is to provide suitable indoor climate conditions for preservation of their collection. In general, a large bulk of hygroscopic material is present which aids stable indoor climate conditions. Limited disturbances due to visitor presence occur in repositories and excludes to a large extent thermal comfort requirements. Library archives show potential of more tolerant setpoint control with permissible fluctuations. Little research is present into dynamic setpoint control and intermittent conditioning in libraries and archives. The aim of this study is to explore the possibility for intermittent conditioning and dynamic setpoint control on the energy impact and microclimate behavior in a library case study in The Netherlands. By means of a hygrothermal monitoring campaign from August 2016 to August 2017 the current indoor climate has been assessed under regular conditions and intervention periods (summer and winter) where the air handling unit was turned off. Both temporal and spatial measurements provided important information on microclimate behavior of the investigated repositories. A validated multi-zone model was used to investigate multiple setpoint strategies. Results show the potential of intermittent conditioning depending on whether dynamic setpoint conditions are used during operational hours (e.g. ASHRAE climate classes). If static conditions are applied, energy demand increases significantly, however, under dynamic setpoint control significant energy savings are possible. The lifetime multiplier is used to assess the chemical risks. The majority of investigated setpoint strategies show increased chemical risk.

1. Introduction

The indoor environment of museums, libraries and archives should provide an adequate indoor climate for the preservation of objects [1]. During the 20th century the notion evolved that a stable indoor climate decreased the risk for object degradation. Incorrect Temperature (T) and Relative Humidity (RH) were identified to be major causes of increased degradation to objects. The rise of Heating Ventilation and Air Conditioning (HVAC) technology resulted in the idea that if a fluctuation in indoor RH of $\pm 5\%$ was good, a fluctuation of $\pm 3\%$ would be better [2]. The general notion for the need of a rather strict indoor climate in museums, libraries and archives is still present today. In order to provide an appropriate indoor environment for a variance of building types and building use, several indoor climate guidelines have been developed in the past decades, e.g. Refs. [3–6]. Taking ASHRAE as an example, the chapter on Museums, Galleries, Archives, and Libraries presents design specifications for different indoor climate classes. These

climate classes include specifications for short-term fluctuations, seasonal adjustments and levels for T and RH. The climate classes range from class AA (precision control) to class D (limited control) and serve as a guideline [7]. Though enough opportunities are presented in various indoor climate guidelines with respect to permissible fluctuations, the notion of a stable indoor climate being the optimum for artifact preservation resulted in many cultural institutions applying a stringent indoor climate class, e.g. ASHRAE class AA. Besides undesired consequences (e.g. condensation risks) in historic buildings [8], it also results in large energy consumption and frequent maintenance of technical components, and hence, high costs [9]. Besides the financial impact, the environmental impact has become an important performance criterion, i.e. becoming more sustainable and reducing the carbon footprint have also become important aspects for heritage institutions. This situation urges for a paradigm shift from the ideal climate to the appropriate climate in order to balance collection preservation, building preservation (in the case of historic buildings),

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Table 1
Building data of the library used for the model.

Dimensions	Zones	Area (m ²)	Volume (m ³)	Height (m)	
Floor 4	3	1961	6667.4	3.4	
Floor 5	4	2667	9067.8	3.4	
Floor 6	3	800	2720	3.4	
Floor 7	3	1489	5062.6	3.4	
Construction	Thickness (m)	λ (W/mK)	ρ (kg/m ³)	c (J/kgK)	R (m ² K/W)
<i>Roof U = 0.24 W/m²K</i>					
Outside					
PVC roofing	0.005	0.17	1300	1470	0.03
EPS insulation	0.14	0.036	35	1470	3.89
Hollow core concrete slab	0.2	1.4	2500	840	0.14
Inside					
<i>Floor U = 0.22 W/m²K</i>					
Finishing					
Finishing	0.01	0.8	1900	840	0.01
EPS Insulation	0.14	0.036	35	1470	3.89
Light concrete	0.05	0.12	400	840	0.42
Hollow core concrete slab	0.2	1.4	2500	840	0.14
Inside					
<i>Exterior walls U = 0.18 W/m²K</i>					
Outside					
Sandwich panel	0.004	200	2800	505	0.00
PUR insulation	0.14	0.026	33	1470	5.38
Reinforced concrete	0.2	1.7	2400	840	0.12
Inside					
<i>Internal walls</i>					
Light concrete slabs					
Light concrete slabs	0.1	0.12	400	840	0.83
Books	#racks-0.25-2.8	0.06	840	750	~

energy performance, and thermal comfort (in the case of museums) [10].

Many studies have focused on the museum environment addressing various aspects such as energy efficiency [11–15], current museum indoor climate [16–19], evaluation of indoor climate on collection preservation [20–22], and thermal comfort of museum visitors [23].

Libraries and archives are less frequently addressed in conservation research combined with indoor climate requirements. The main differences compared to the museum environment are the infrequently accessed repositories by visitors or employees and the often vast amount of hygroscopic materials present. A myriad of studies relate to the moisture buffering of building materials and interior materials, e.g. Refs. [24–26]. This resulted in more detailed studies on the moisture buffer capacity of specific collection types which can be found in archives and libraries [27,28].

The combination of little disturbances and a naturally stable indoor climate limits the need for active climate control systems. Improved energy efficiency and less technology dependency may be provided by (i) passive measures, (ii) intermittent conditioning. Passive climate control in archives shows potential, however, ventilation or recirculation is needed to control internally generated pollutants [29]. In Denmark, several passive archives or storage buildings are constructed with external walls with high thermal and hygroscopic capacity and good insulation capacity. These buildings show the potential of passive measures [30,31]. Less technology dependency is investigated by turning off the air handling unit (AHU) creating intermittent conditioning, and provides generally positive results according to the study of [32].

Though many guidelines include different conservation purposes such as museums, galleries, archives and libraries, the number of guidelines providing specific specifications for archives and library repositories is limited. Velios [4] mentions their proposed specifications as suitable for both storage and display conditions. ASHRAE [5] provides a table with different climate classes including classes for cold and cool storage, however, only related to chemically unstable objects.

National regulations describing indoor environment specifications for national archives stem often from the idea of stringent indoor climate conditions, e.g. the Dutch Archival Legislation with T is 18 ± 2 °C and $50 \pm 5\%$ RH [33]. Research showed the potential of archives and libraries to maintain a stable climate though striving for improved energy efficiency and less technology dependency. The aim of this study is to explore the effects of intermittent conditioning and dynamic setpoint control on the energy demand in a Dutch library case study. The resulting indoor environment will be analyzed to assess possible risks to the present archival collection.

Section 2 explains the used methods including a description of the case study, data acquisition of the experimental and computational study, and the used climate control scenarios. Section 3 and 4 present the results of the measurement campaign, the microclimate analysis, and the results of the computational modeling. The energy impact of the indoor climate scenarios and the evaluation of the indoor climate with respect to object preservation is illustrated to propose a suitable climate control strategy for library archives. Section 5 provides a discussion and concluding remarks.

2. Methodology

In order to gain insight into current practices and improved climate control practices a Dutch case study was used in an experimental and a numerical study.

2.1. Case description

The building under investigation is anonymized and necessary details are described in this section. The building is located in The Hague, the third largest city of The Netherlands and part of a heavily urbanized area called the Randstad. Besides a public function, the case study library has primarily the task to preserve a copy of every book that has been published in or about The Netherlands. This results in a building largely existing of a repository to preserve over seven million books,



Fig. 1. Floorplan with measurement positions and zonal distribution.

newspapers, magazines and micro materials covering a time span from the Middle Ages until today. The collection is partly housed below ground level and partly in a four floor building. This study focuses on four floors above ground level which are constructed in such a way that this tower is situated above a tram line. The investigated repository is constructed with steel columns penetrating the different floors acting as thermal bridge on the fourth floor. Further structure materials for the repositories can be found in Table 1 and an exploded view of the floor plans in Fig. 1.

The repositories have a very small heat and moisture load due to people. They are visited three times a day by employees, with varying dwelling times. In order to keep the indoor T and RH as stable as possible and eliminate sudden fluctuations, an all-air HVAC system is used. The AHU consists of a cooling coil, heating coil, humidifier and fan. The four floors have individual reheating and recooling coils to adjust the air temperature to meet the setpoint at every floor. In the reference case, the setpoints were 18 °C for T and 55% for RH all year round.

2.2. Experimental campaign

An experimental campaign was set-up to assess the present indoor environment. From august 2016 to august 2017, continuous measurements of T and RH have been performed on floors 4 to 7, each floor consisting of two in-use repository zones. Outdoor measurements consisted of air temperature, relative air humidity, and solar irradiance. Eltek measuring equipment has been used with combined T and RH sensors providing a measurement accuracy of ± 0.4 °C and $\pm 2\%$ RH. The sensors have been calibrated by the Building Physics and Systems Laboratory of the Eindhoven University of Technology. Calibration of temperature and humidity sensors is performed to check the accuracy of the equipment. The data of the sensors will be compared to a very precise reference sensor (calibrated by the NMi; Nederlands Meetinstituut). The sensors are placed in a special climate chamber in

which a temperature and humidity trajectory is imposed. A polynomial function containing calibration constants is the result of the relation between the sensor and reference sensor. This function is used to convert the measurement data in the database to be as accurate as possible. After calibration the overall accuracy of the sensors is slightly better than the accuracy provided by the manufacturer. An Eltek RX250AL data logger was used to collect, store and send data to a server at Eindhoven University of Technology. The sampling interval was 10 min. On floor 6, an extensive measurement grid has been set up, see Fig. 1. Spatial differences of T and RH have been measured both horizontally and vertically. This was done to investigate the homogeneity of the investigated areas. The horizontal grid was situated in such a manner that near the building envelope, near the bookshelves, and in between the shelves at a height of 1.60 m measurement equipment was located. The figures presented in section 3.3 are constructed with a Matlab script in which the sensor data is used as output to create a contour plot. The vertical stratification measurement was performed at positions 13 and 14 at heights of 0.12 m, 1.60 m and 2.60 m.

Everyday operation of the library's repository was monitored and considered to be a reference. Two intervention experiments were conducted: (i) During the summer period from August 29 to September 2, 2016; (ii) during the winter period from December 12 to December 16, 2016. During these intervention periods the AHU of the repository was turned off and the indoor climate was closely monitored during this free floating situation. As soon as the indoor climate in the repository reached the maximum or minimum permissible T or RH, the AHU was activated to maintain climate conditions that fit the original boundary conditions.

2.3. Numerical modeling

Numerical modeling was used to study the effect of different climate control strategies and keep risks for the collection to a minimum. The Heat, Air and Moisture modeling tool, HAMBASE, was used to develop a multi-zone model of the library environment [34,35]. HAMBASE is developed in the MATLAB environment where indoor T, RH and energy consumption have been simulated in the model. Energy consumption has been simulated for heating, cooling, humidification and dehumidification. More extensive information on HAMBbase modeling is given in the appendix of [22].

The HAMBbase model consists of three zones representing the 6th floor. Zones B and C are used as filled repositories and have been extensively monitored in the experimental campaign. Zone A is empty and reserved for possible expansion of the current collection. Employee presence was determined by visual observation. Moisture gains from these employees were set to 270 g/h as their work mostly consists of walking with a certain weight. Since there are no employees continuously working in the repositories, moisture gains were limited to 10 min/h to create an intermittent pattern in employee presence [36]. Casual thermal gains including heat from lighting fixtures and gains by employee presence also were created with an intermittent pattern resulting in 10 W/m² and 80 W per present employee per full hour. On average the percentage of fresh outdoor air is 10% of the total ventilation air (21820 m³/h averaged per floor), 90% is recirculated air. Since there are so few people present in the zones it is not needed to increase the ventilation rate and it is therefore kept low during the operational hours of the library. Table 1 shows the used building data for the model.

The collection forms a substantial part of the heat and moisture capacity which stores and releases heat and moisture. Internal walls are used to model the collection. The material properties of paper have been assigned to these internal walls. Properties such as thermal conductivity (W/mK), density (kg/m³), specific heat capacity (J/kgK), and emissivity (–) are based on literature studies [27,37]. The moisture

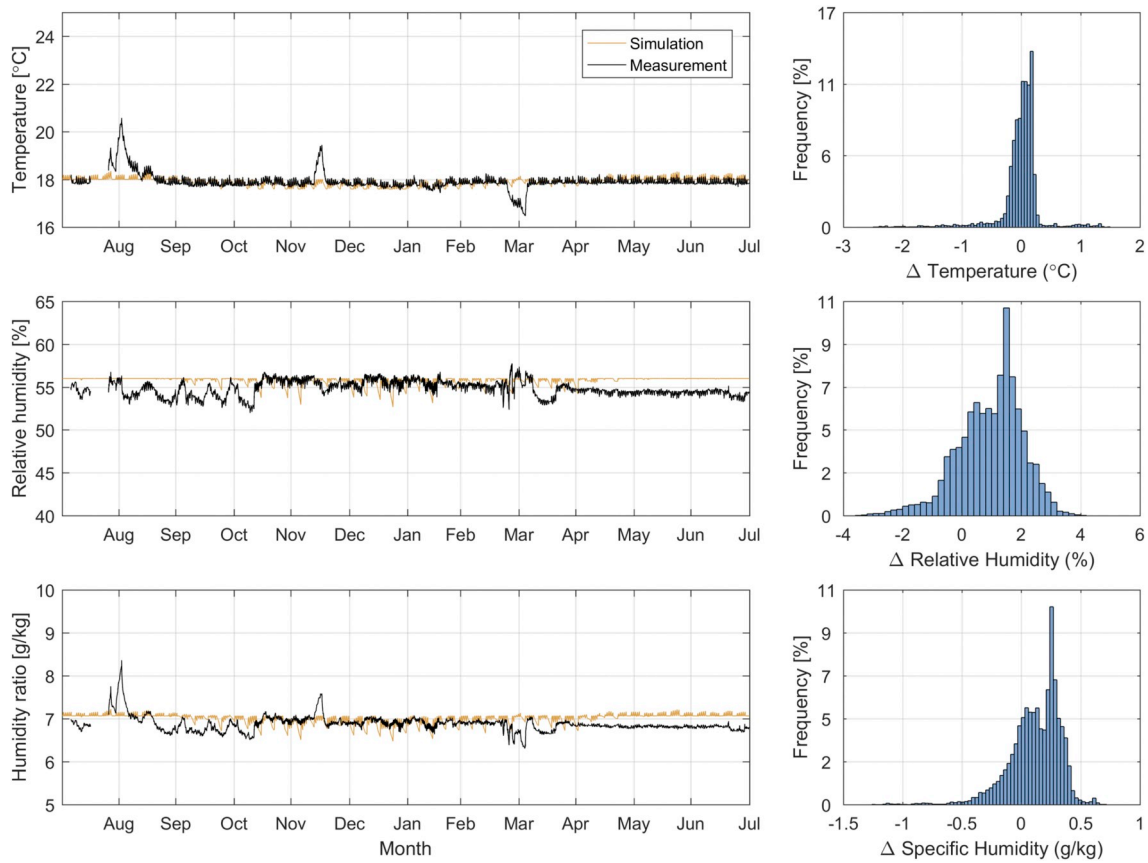


Fig. 2. Comparison between measurement (black) and simulation (orange) in zone B over one year under normal operating conditions (left) and the frequencies of the variations between measurement and simulation (right). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

properties of paper, like the diffusion resistance factor μ (–), specific moisture capacity related to relative humidity ξ (kg/m^3) and water vapor effusivity b_v ($\text{s}^{3/2}/\text{m}$) were calculated (see Appendix A).

Energy weather data for Amsterdam, The Netherlands have been retrieved from the EnergyPlus Weather Database [38]. The typical weather data is specifically used for the energy simulations of the different scenarios and consist of IWEC data. IWEC comprise multiple years of climate data to represent typical weather conditions of a location. The database weather files were converted to the correct file format for HAMBASE. Global radiation was split to direct and diffuse radiation using the Perez model. The file format uses the following data: diffuse solar radiation, air temperature, direct solar radiation, wind speed, wind direction, relative humidity outside, duration rainfall, summation hourly rainfall, cloud cover.

2.4. Model validation

Validation of the building simulation model was performed using data collected with the experimental measurements. Fig. 2 compares measurements to simulation results of the indoor T, RH and specific humidity (SH) for zone B. The measured data is based on an average of all the present sensors in zone B, because HAMBbase calculates an average temperature and RH for each zone. The histograms on the right side of Fig. 2 show the frequency of deviations between measurements and simulation. It shows that the model overestimates RH and SH values while the T deviations are small. The graphs on the left side show that, during the simulation of the entire year, the model slightly overpredicts T and RH in Summer and underpredicts T in Winter. The peaks

that can be observed in Fig. 3 during August, December and March are related to intervention periods. The March intervention period used active cooling and was omitted from this study due to different study objectives. The numerical model used to validate these periods is shown in Fig. 3.

The intervention periods have been separately simulated with different control settings than the regular operational use of the HVAC system. Fig. 3 compares measurements and simulation results of the intervention. The intervention simulations show that during the free-floating period both T and RH show the same trend as the measurements. Both during summer and winter intervention it is shown that T increases, RH remains unchanged, and specific humidity increases.

Table 2 provides model calibration results based on the statistical indices cumulative variation of the root mean squared error (CV RMSE) and the mean bias error (MBE) (see equations (1) and (2)). These indices are used for model accuracy of the building simulation compared to measurement data [39].

$$MBE(\%) = \frac{\sum_{i=1}^{N_p} (m_i - s_i)}{\sum_{i=1}^{N_p} m_i} \quad (1)$$

$$CV \text{ RMSE}(\%) = \frac{\sqrt{\sum_{i=1}^{N_p} (m_i - s_i)^2 / N_p}}{\bar{m}} \quad (2)$$

Where m_i are the measured data points for each model instance i , s_i are the simulated data points for each model instance i , N_p is the number of data points at interval p and \bar{m} is the mean of the measured data points.

Models are considered calibrated if they comply with criteria set out

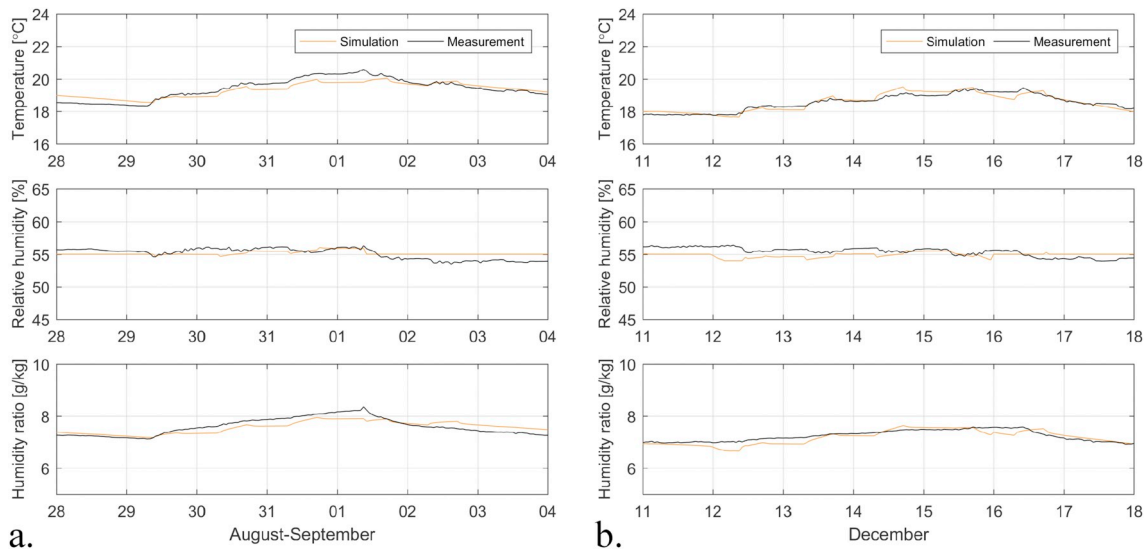


Fig. 3. Measurements compared to simulation results of the indoor climate conditions during two interventions: (a) Summer, (b) Winter.

Table 2
Model calibration based on statistical indices CVRMSE and MBE.

	T (°C)		RH (%)		x (g/kg)	
	CV RMSE (%)	MBE (%)	CV RMSE (%)	MBE (%)	CV RMSE (%)	MBE (%)
Zone A	0.99	-1.04	0.74	0.78	0.36	-0.38
summer intervention	0.40	-0.40	1.13	1.13	0.85	0.85
winter intervention	5.47	-5.50	5.45	5.48	0.66	-0.66
Zone B	0.01	0.01	2.24	-2.34	2.25	-2.35
summer intervention	0.40	-0.40	0.36	-0.36	0.81	-0.81
winter intervention	5.45	-5.48	6.79	6.83	0.87	0.88
Zone C	2.85	2.89	0.15	0.16	3.29	3.44
summer intervention	5.94	5.59	7.67	-7.97	0.44	-0.44
winter intervention	2.61	-2.61	6.90	6.91	4.10	4.12

by ASHRAE guidelines 14 [40]. Attaining a 10% MBE and a 30% CV RMSE using hourly data is considered a calibrated model. Though the ASHRAE guideline 14 is mainly used to evaluate energy models, an agreed upon standard for hygrothermal performance simulations is not present yet. The model used in this study is considered calibrated (see Table 2).

2.5. Scenarios

In order to model intermittent conditioning and dynamic setpoint control, several scenarios have been developed. With the validated model these scenarios were simulated to gain insight in the potential energy impact and indoor climate behavior.

- The first modeled scenario is the reference scenario. The environmental specifications of the case study were used: 18 °C for T and 55% for RH.
- The second scenario uses permissible short-term fluctuations for T and RH according to the Dutch Archival Legislation [33]. This bill was first defined and approved in 1995 and has since then not changed. The legislation uses the setpoints $18 \pm 2 \text{ °C} / 55 \pm 5\%$ for the preservation of specific materials like paper, parchment, wax, leather, textile, wood, paper black and white photo material, and optical discs. Certain other materials have defined indoor climate specifications but are not considered in this study.

- Multiple setpoint strategies are made for modeling intermittent conditioning. Intermittent conditioning implies that for periods of time the AHU is turned down resulting in a free floating indoor climate. This study considers closing hours in the weekends as an appropriate period to turn down the AHU when no disruptions from employees are present. From Friday 06:00PM till Monday 00:00AM the AHU is turned down. This decision is based on the experimental results of the intervention period which were performed during Monday till Friday when disruptions (e.g. employees) were present. The simulation scenario models the operational hours of the HVAC system upon the strict reference and ASHRAE climate classes (AA, As, A, B) requirements, during non-operational hours of the AHU, no T and RH setpoints are imposed.
- The last scenario is based on the dynamic setpoint control algorithm developed in Ref. [12]. This algorithm consists of several steps to determine suitable indoor climate specifications for T and RH introducing the concept of controlled fluctuations. Temperature is mainly based on visitor thermal comfort and RH is regulated by collection requirements. The algorithm starts with determining when visitor thermal comfort in museums [23] overrules the T limits for collection requirements [5] and vice versa. RH limits are determined by the collection requirements based on the ASHRAE climate classes. Since the current study does not take visitor or employee presence into account, collection requirements is considered leading. Dynamic setpoint control results in an upper and

Table 3
Overview of used T and RH setpoints and allowed short-term fluctuations and seasonal adjustments.

		T[°C]			RH[%]		
		fluctuation			fluctuation		
		T _{sp}	short-term	seasonal adjustment	RH _{sp}	short-term	seasonal adjustment
Scenario 1	Reference	18	–	–	55	–	–
Scenario 2	Dutch Archival Legislation	18	± 2	–	50	± 5	–
Scenario 3	Intermittent	FF ^a	–	–	FF	–	–
A	strict	18	–	–	55	–	–
B	AA		± 2	± 5	–	± 5	–
C	As		± 2	+5/-10	–	± 5	± 10
D	A		± 2	+5/-10	–	± 10	–
E	B		± 5	+10	–	± 10	± 10
Scenario 4	Dynamic control		± 2	± 5	–	± 5	–

^a Where FF stands for Free Floating and the climate classes are based on [5].

lower limit with no predefined static setpoint. This allows the indoor climate parameters to vary freely in between these limits resulting in a T and RH range. Since ASHRAE provides two archive climate classes, i.e. cool and cold storage, which do not apply to the case study preservation environment, the indoor climate specifications were determined by ASHRAE climate class AA. With the allowed fluctuations of ± 2 °C and ± 5% RH, climate class AA is in line with the Dutch archival legislation fluctuations.

Table 3 provides the T and RH setpoints of the different scenario's including short-term fluctuations and seasonal adjustments. Fig. 4 provides a visual overview of the used scenarios. The intermittent scenario is represented by the use of strict climate specifications during operational hours.

3. Experimental results

The climate data that are measured were analyzed both in the temporal and spatial domain. The degradation risk of the collection

were evaluated based on object analysis.

3.1. Microclimate analysis

Fig. 5 depicts the outdoor climate conditions during the summer and winter intervention periods for T, RH and specific humidity. Summer outdoor conditions included warm days with temperatures of 25 °C and high peaks in solar irradiance. Winter conditions show temperatures below 10 °C and limited solar irradiance. RH during summer showed a strong day/night cycle between 50% and 95%. During winter RH was constantly above 75%.

Fig. 6 shows the results of the indoor climate measurement campaign during the summer and winter interventions. It shows a significant difference between the lower three floors and the upper floor. This phenomenon was not only present during the interventions but throughout the entire measurement period. Internal heat sources such as an adjacent technical room, and the large roof area exposed to solar radiation could be of influence on the indoor climate during the measurements of floor 7.

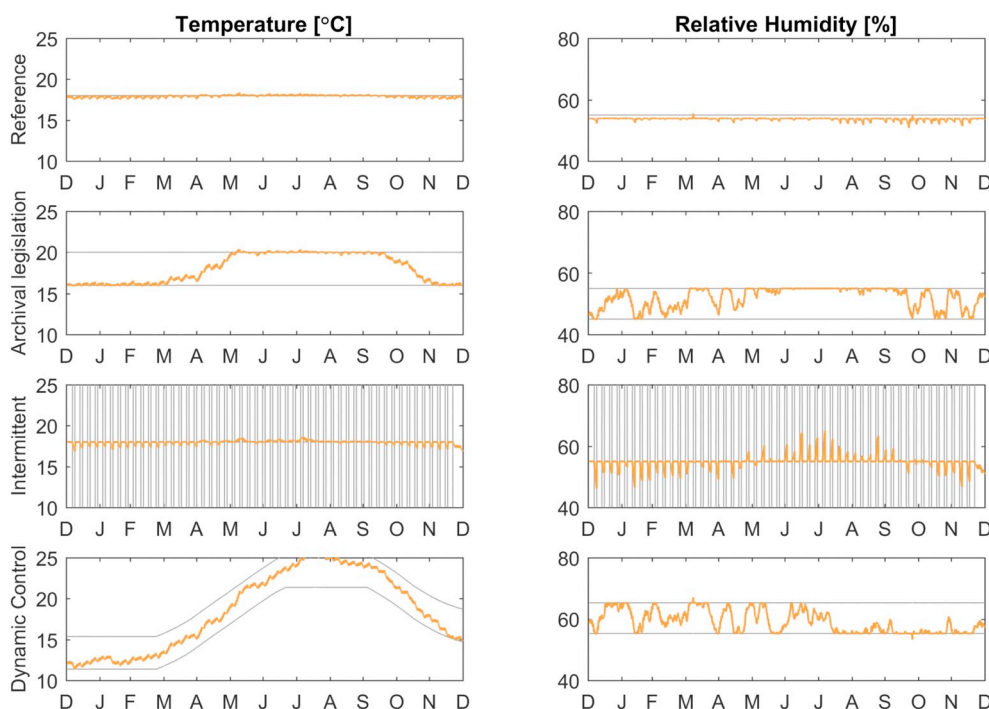
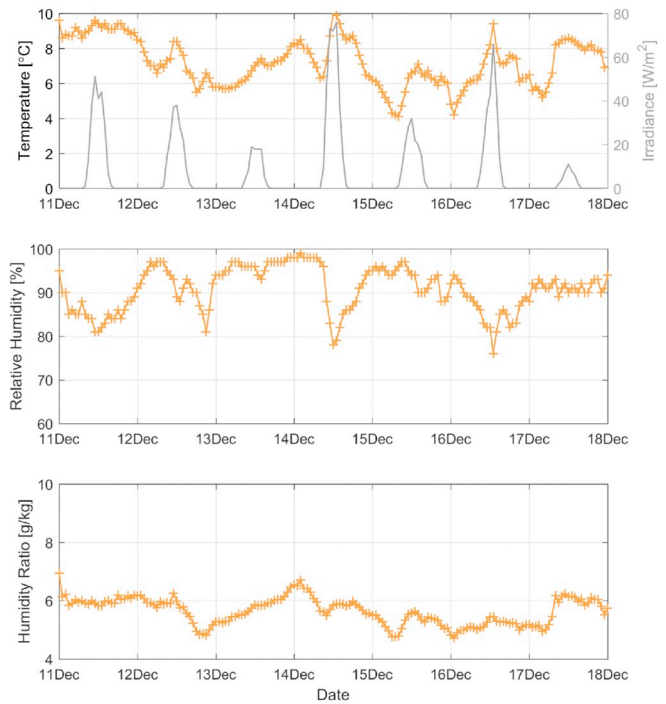
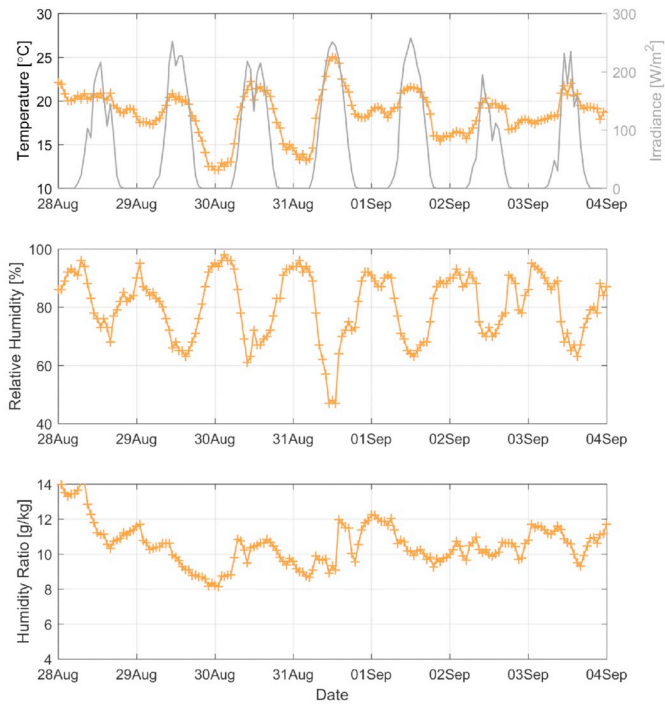


Fig. 4. Overview of different setpoint strategies for temperature and relative humidity. The indoor climate conditions (orange curve) and setpoints, minimum and maximum, (grey curves) are depicted for different scenarios. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)



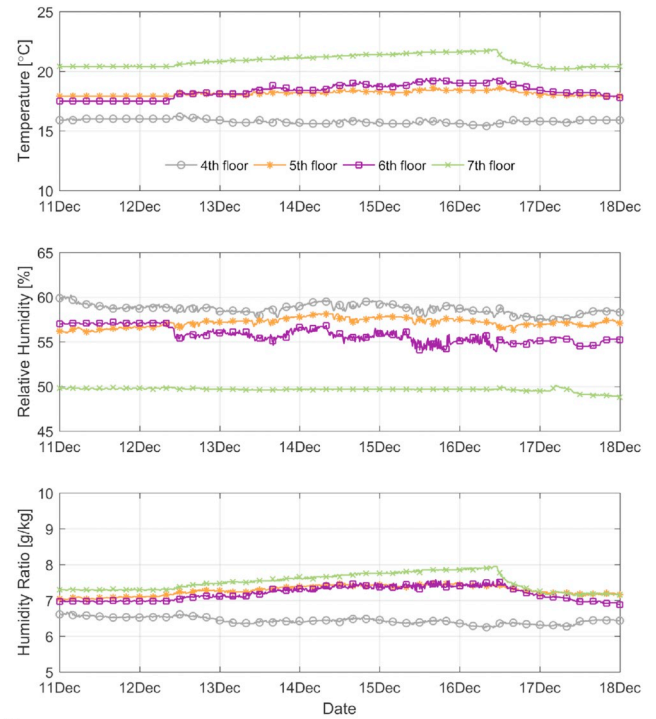
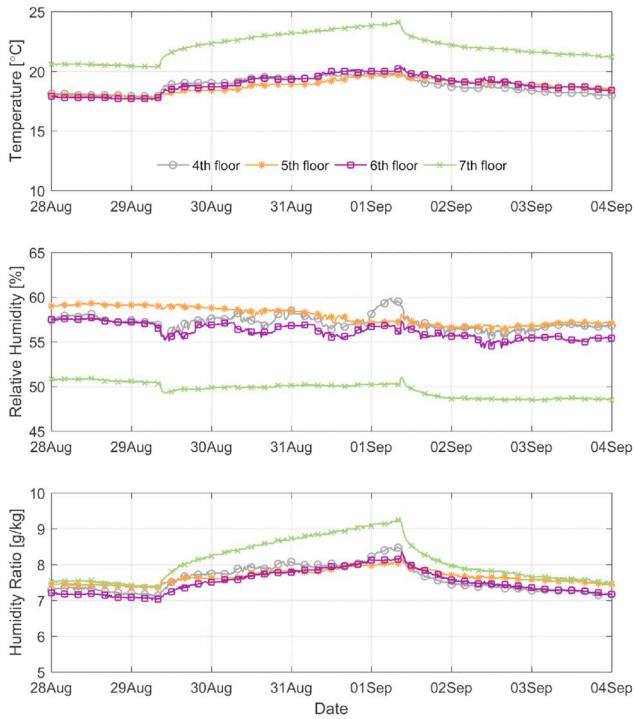
a.

b.

Fig. 5. Outdoor climate conditions during summer (a) and winter (b) intervention periods.

During the summer intervention, indoor temperature increased steadily over the measurement period. This is expected during a summer period. During the intervention it was expected that the relative humidity would decrease over time. However, RH remained stable, presumably due to the presence of large hygroscopic mass

provided by the paper collection. The collection desorbed moisture which can be seen by an increase of the humidity ratio, see Fig. 6 bottom. The absolute moisture in the air increased together with the temperature which means moisture is released from the collection to the indoor air. Both in Summer and in Winter interventions, the



a.

b.

Fig. 6. Indoor climate of floor 4–7 during the summer (a) and winter (b) intervention.

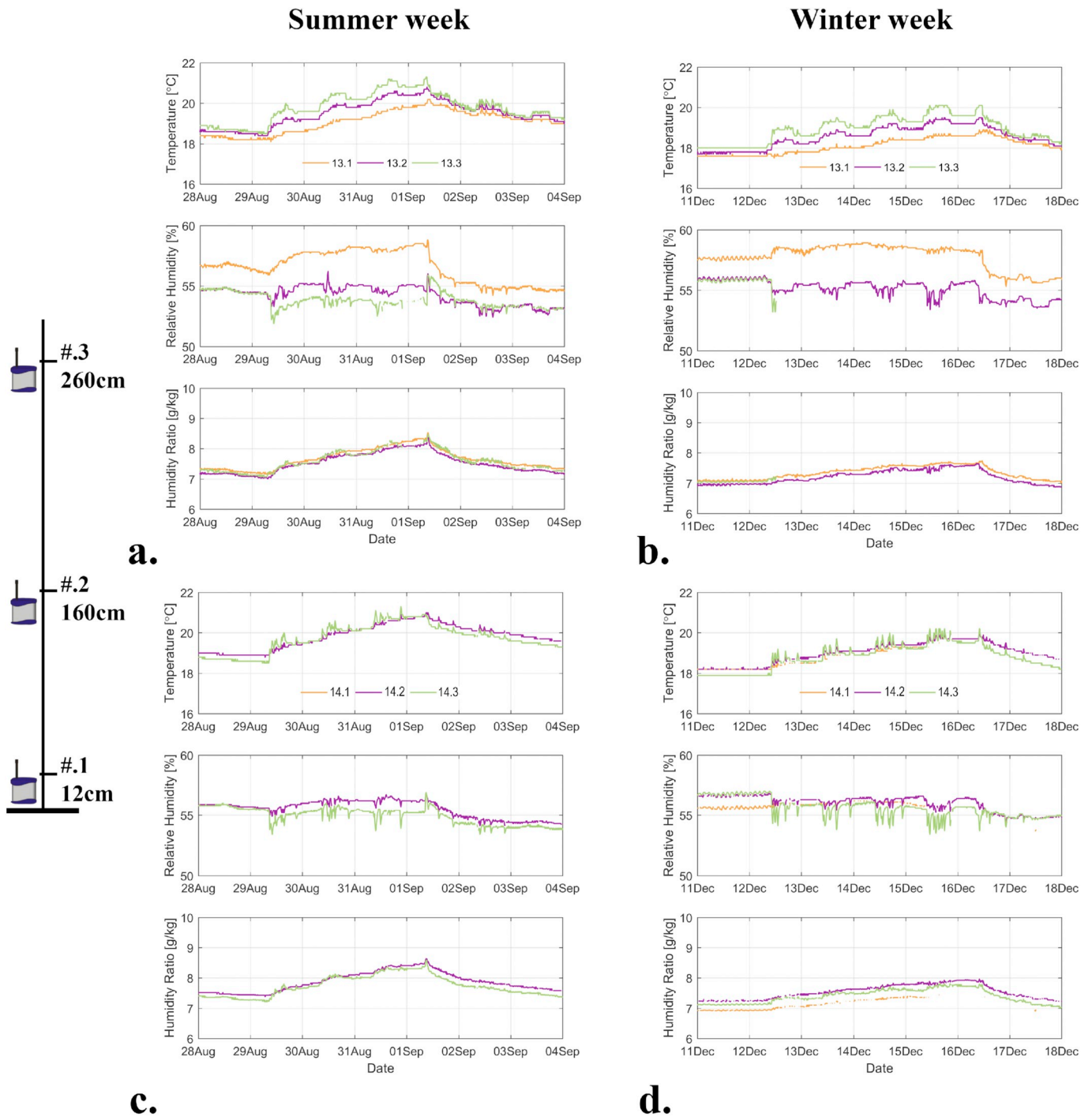


Fig. 7. Spatial stratification results for summer and winter intervention periods. Both near the building envelope (a–b) and near the book shelves (c–d) measurements were performed.

collection presence is responsible for a stable indoor RH. It took around 3–4 days before the temperature to increase with 2 K.

3.2. Spatial measurements in the vertical plane

Near the building envelope and near the bookracks, vertical stratification measurements were performed. Fig. 7 shows the measurement results. Summer intervention (Fig. 7a, c) and winter (Fig. 7b, d)

intervention show an increase in temperature and specific humidity throughout the intervention periods. RH remains fairly stable throughout both interventions.

Stratification measurement 13 near the external wall (Fig. 7a and b) shows a larger vertical gradient for T and RH than measurement 14 which is located near the bookshelves (Fig. 7c and d). This occurs when the AHU is turned off. This shows that thermal convection due to buoyancy is the driving force for mixing the air near the building

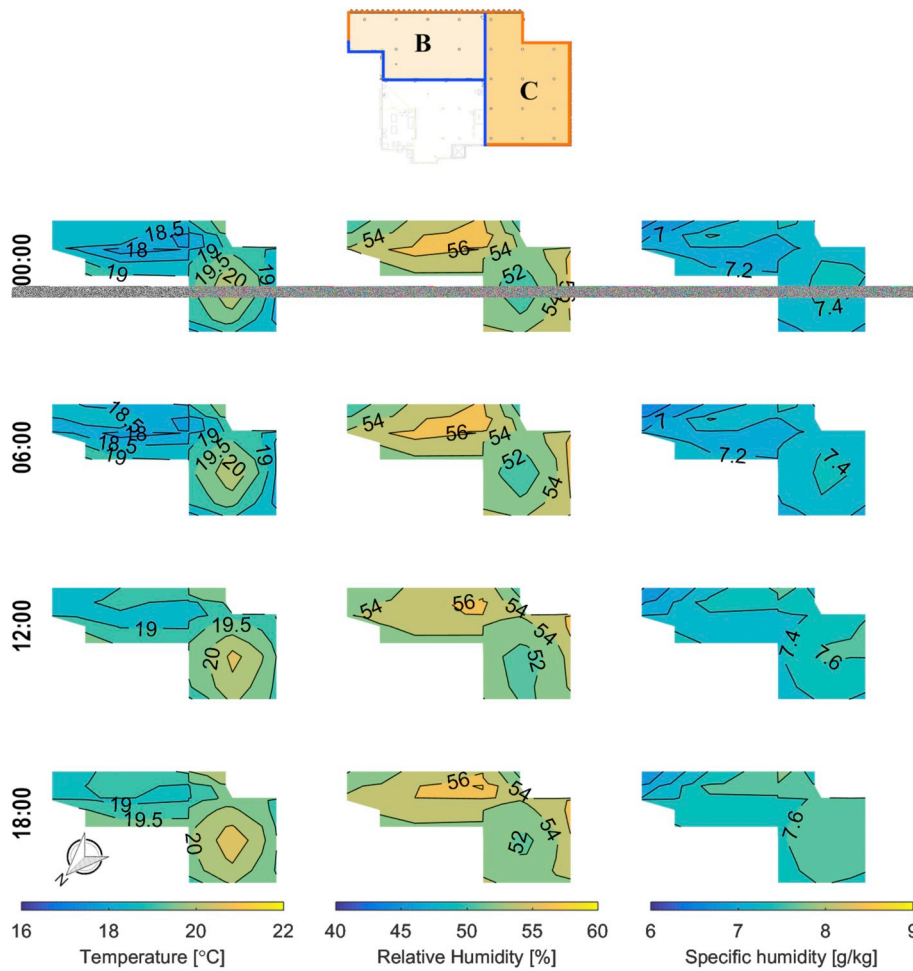


Fig. 8. Top; schematic view of important areas and walls. Spatial distribution of indoor temperature (left), relative humidity (middle), and specific humidity (right) during the first day of turning AHU off at 9.00 h. Date Monday 29-08-2016.

envelope. The indoor climate conditions near the collection show less spatial differences during the interventions.

3.3. Spatial measurements in the horizontal plane

T and RH data were collected with a 10 min time-interval over the period of a year. This gives insight in the temporal behavior over different seasons and intervention periods. The vertical stratification provides insight in the behavior near the building envelope and near the collection in the vertical plane. Moreover, during the experimental study a horizontal measurement grid was also installed on floor six zone B and C, which consists of twenty combined T/RH sensors and provides spatial information on the distribution of the indoor climate conditions that were measured. The measurement grid is indicated in Fig. 1, and provides 52560 data points per location per variable. Fig. 8 presents the results of the day that intermittent conditioning started during the summer intervention. The AHU was turned down at approximately 09.00 h. The difference between each isoline is 0.5 K for temperature, 2% for RH, and 0.2 g/kg for specific humidity. In Fig. 8 the plots are presented for every 6 h. The schematic floorplan at the top shows the two zones and the external walls (orange) and internal walls (blue). It shows the trend of T slightly increasing during the day and the gradient present in the upper image decreases over time from $\Delta T = 2^\circ\text{C}$ to $\Delta T = 1^\circ\text{C}$ in the lower left image. RH remains stable and a slight

increase in specific humidity is shown in the middle and right columns. On an hourly bases very slow changes are visible.

Fig. 9 and Fig. 10 show the spatial distribution during the summer and the winter intervention. On Monday the AHU was turned off and on Thursday at approximately 10.00 h the AHUs were set to normal operational use. These figures provide insight in critical areas in the storage spaces during intermittent conditioning and during normal operational HVAC use. Zone C, which has a few large exterior walls facing South-West (see Fig. 8, schematic floorplan for wall definition), shows a larger increase in temperature during the summer intervention mainly caused by solar irradiation on the external walls. Overall, T increases at every location while RH stabilizes over time. Specific humidity shows an increase in gradient near the North-East wall of Zone B.

During Winter intervention both T and specific humidity increase when the AHU is turned off. Compared to Summer intervention the T gradient is lower during Winter intervention. RH remains stable in both situations.

4. Numerical results

Building simulation allows analysis of the energy impact of the modeled scenarios. Climate risks to the collection are analyzed using the specific risk assessment [20] and the measured T and RH data.

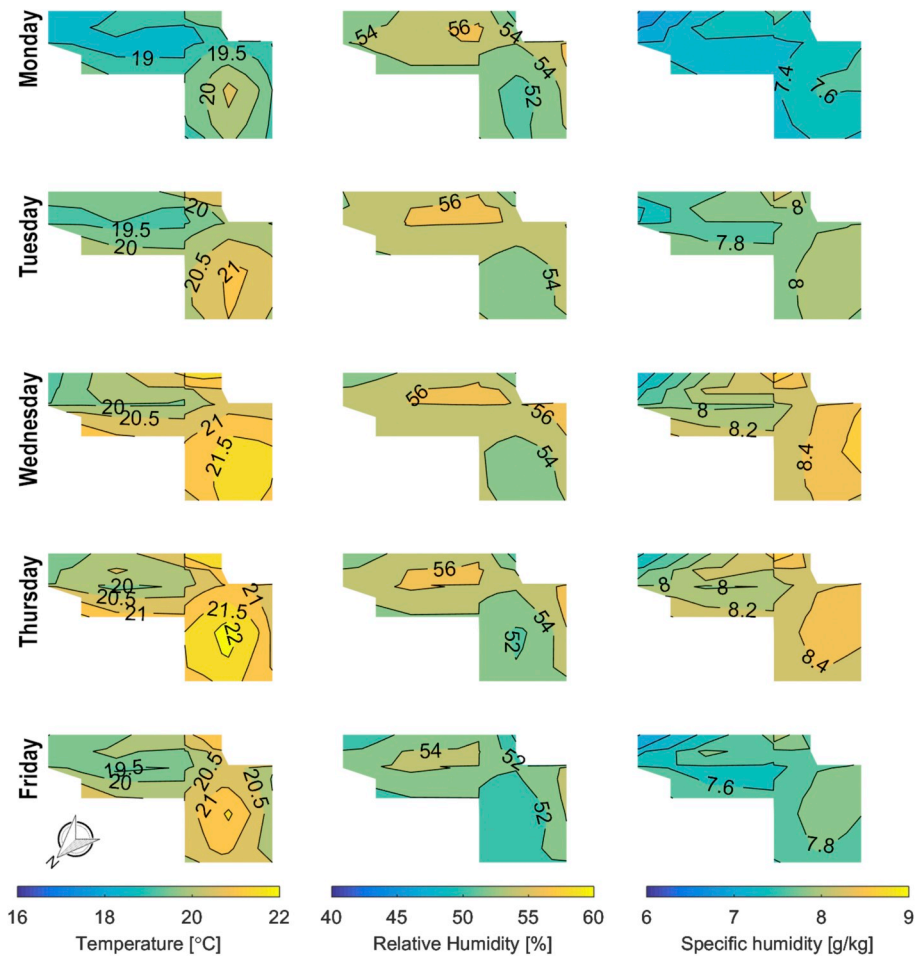


Fig. 9. Spatial distribution of indoor temperature (left), relative humidity (middle), and specific humidity (right) during the summer intervention week.

4.1. Energy impact

Fig. 11 shows the results of the scenarios simulated with the computational model on the energy impact during a reference year. Table 4 provides the absolute numbers of the energy consumption for each scenario. The AHU is constantly correcting small deviations from the rigid setpoints of T and RH specifications of 18 °C and 55%. This results in a large energy demand for cooling and dehumidification.

Using the Dutch Archival Legislation effectively by allowing permissible ranges for T and RH fluctuations the energy consumption for climate conditioning would be reduced by 40% for Zone B.

The first intermittent conditioning strategy shows an increase of approximately 60% in energy consumption compared to the reference case. The T and RH requirements during operational use are based upon the strict setpoints of the reference used in the case study (T = 18 °C and RH = 55%). During the period the AHU is off, the free floating condition start to fluctuate from these strict setpoints. This results in constantly cooling or heating back the free floating conditions at full capacity to these strict specifications when the AHU is turned on. When a more tolerant setpoint strategy can be realized during the operational hours, this could lead to large energy reductions. Applying ASHRAE climate classes (AA-B) during operational hours show a significant reduction in cooling, heating and dehumidification energy demand (see Table 4). Climate class AA shows that humidification has the largest share in energy demand. This is due to the relatively small bandwidth

compared to climate classes A and B. Class A has a seasonal adjustment which reduces this humidification energy demand to a certain extent, however, class A shows that a wider range in relative humidity setpoint decreases energy demand more.

Dynamic setpoint control is based upon the ASHRAE climate classes and a reduction in energy demand is expected. Fig. 11 shows an energy reduction of 93%.

A wider bandwidth for T and RH setpoints provides possibility to introduce permissible fluctuations. The AHU needs to condition less which results in high energy reduction compared to the tight bandwidth the case study currently allows.

4.2. Indoor climate evaluation

Energy consumption results look promising for strategies based on climate which allows a larger bandwidth. However, it is important to relate the simulated indoor climates to possible risks for object degradation. With the climate evaluation chart (CEC), which has been introduced by Martens [20], an evaluation has been made for both the reference setpoint control and dynamic setpoint control. The CEC plot, see Fig. 12, shows the indoor climates plotted in a so-called psychrometric chart. The thick green line represents the mold curve developed by Adan [41].

Fig. 12 shows the results of four scenarios. The reference case (grey) is concentrated around the strict setpoints. The archival legislation

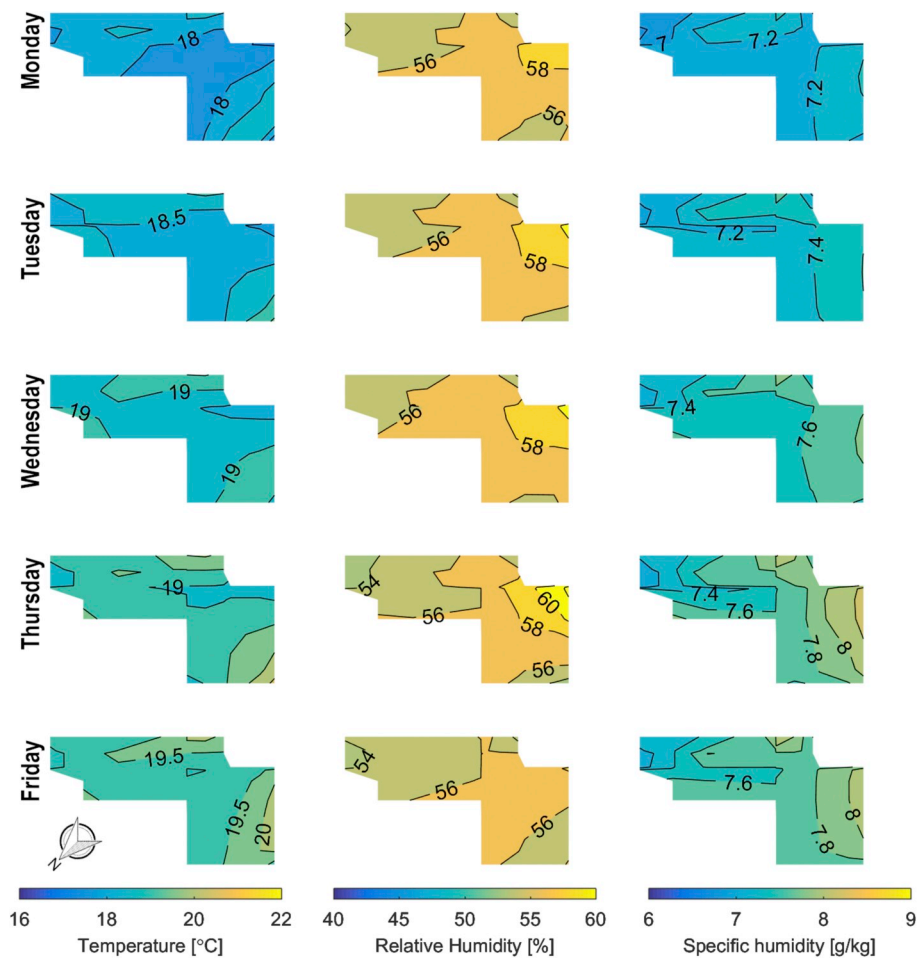


Fig. 10. Spatial distribution of indoor temperature (left), relative humidity (middle), and specific humidity (right) during the winter intervention week.

scenario (magenta) shows a wider spread for T and limited spread for RH. Both intermittent conditioning (green) and dynamic control (orange) show a wide spread for both T and RH. All other scenarios are within these limits.

Fig. 13 shows the histogram plots for all investigated scenarios. They represent the mean values with standard deviation σ plotted as error bar of the hourly and daily fluctuations of indoor temperature and relative humidity.

The reference illustrates that fluctuations of the indoor climate were very small. The fluctuations of T per hour or per day are 0.2 °C or smaller. RH hourly and daily fluctuations are 1% or smaller.

Intermittent conditioning scenarios AA – B and dynamic control show similar trends concerning the daily and hourly fluctuations per season. This means that for temperature the values are increasing with seasonal adjustment in a stable manner and not exceeding short-term fluctuation limits. Hourly and daily fluctuations of RH, although slightly larger deviations than the reference study, did not exceed short-term fluctuation limits.

4.3. Object damage risks evaluation

An object evaluation has been carried out with the specific risk assessment developed by Martens [20]. Though the specific risk assessment is available for four typical museum objects, the library collection consists mainly of paper and books. Fig. 14 provides the results of the assessment for paper based objects. It shows that the indoor

climate does not increase the risk for mold degradation. Measurements for all scenarios are not exceeding the germination limits.

The lifetime expectancy is based on the isoperm method developed by Sebera [42]. This method quantifies the effect of T and RH on the lifetime of a paper based collection compared to a reference condition of 20 °C and 50% RH. Michalski used this method to define the lifetime multiplier (LM) [43]. Since ASHRAE climate class A is based on collection requirements in museum exhibition rooms, it is expected that the dynamic control scenario will have a lower LM since T and RH are higher than the reference case. Currently, the ASHRAE climate classes for archives and libraries are limited to cold and cool storage classes. Fig. 14 shows that the LM for the reference case stays over 1 the entire year, resulting in environmental conditions for T and RH where the collection exceed its lifetime compared to the reference conditions of 20 °C and 50% RH. The LM for the archival legislation case drops below LM = 1 during the summer months. During winter the LM increases and the equivalent LM (LMe) is 1.19 for this scenario. The intermittent conditioning and dynamic control scenarios show similar trends. Summer months, during which the temperatures rise, show low LM values. Winter provides a significant rise in LM. The LMe for these scenarios is within 0.79–0.89.

5. Discussion and conclusions

With an AHU in operational use, the investigated repository shows small gradients in T and RH. The injected air seems well-mixed and

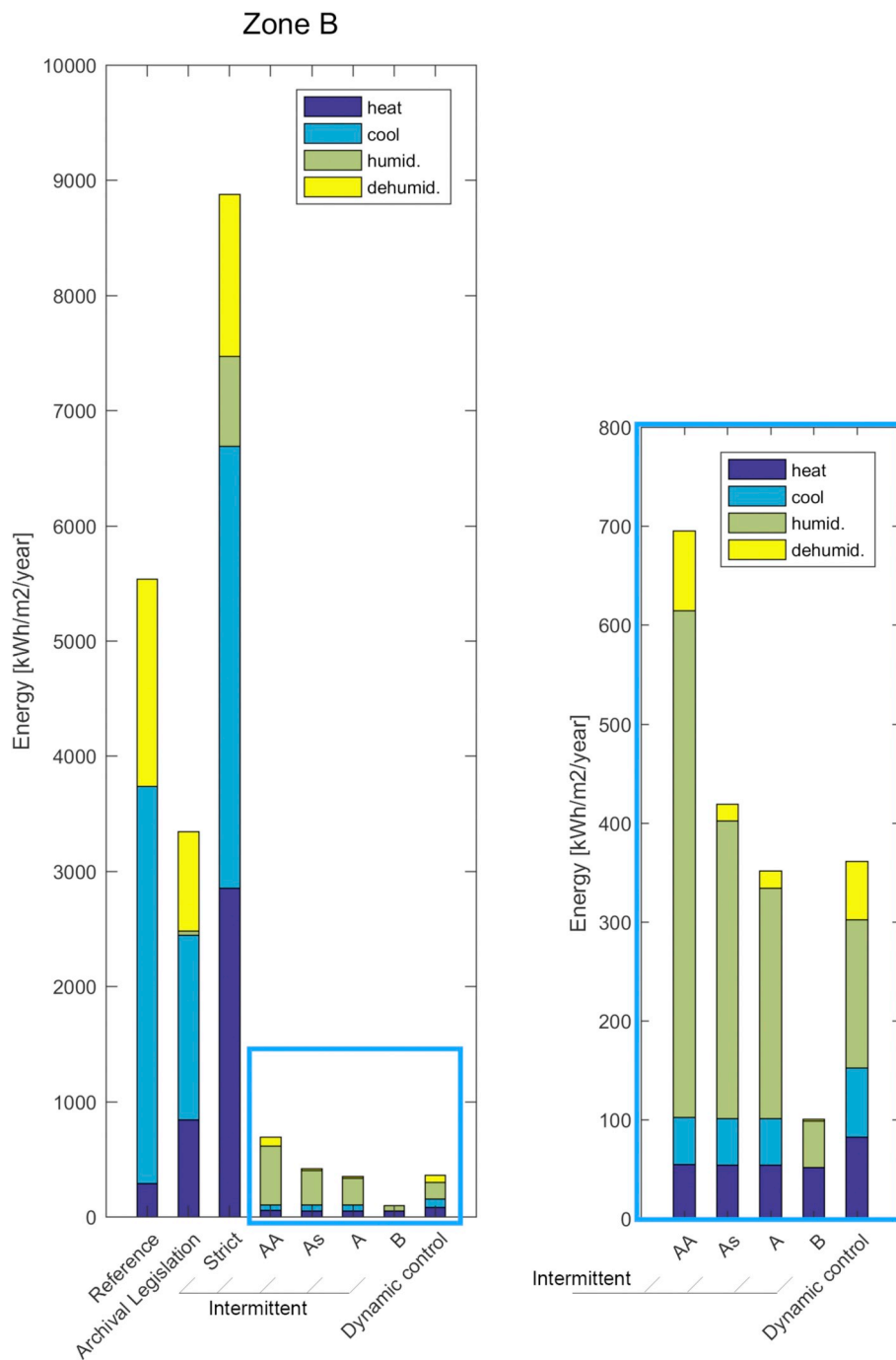


Fig. 11. Energy impact for eight different scenarios for Zone B.

Table 4
Detailed energy demand of different setpoint strategies for Zone B.

	E [kWh/m ²]			
	Heating	Cooling	Humidification	Dehumidification
Reference	290	3448	0	1802
Archival legislation	841	1602	37	867
Intermittent				
Strict	2856	3833	785	1404
AA	55	47	512	80
As	54	47	301	17
A	54	47	234	17
B	52	0	47	2
Dynamic control	83	70	150	59

results in homogeneous air conditions for the present collection. Per investigated floor the air conditions are different, the upper floor shows a significant higher indoor T during the measurement campaign. An increase in indoor T was not expected during the winter intervention period. The external climate conditions with lower T cannot explain this observation. Simulating the winter intervention also showed this increase of indoor T. Internal heat exchange between different zones might be causing this since offices are kept at higher T to ensure employee thermal comfort.

Fluctuations in T and RH during the interventions are small and acceptable during both intervention periods. Indoor T slowly increases and indoor RH remains stable, indicating the moisture buffering effect

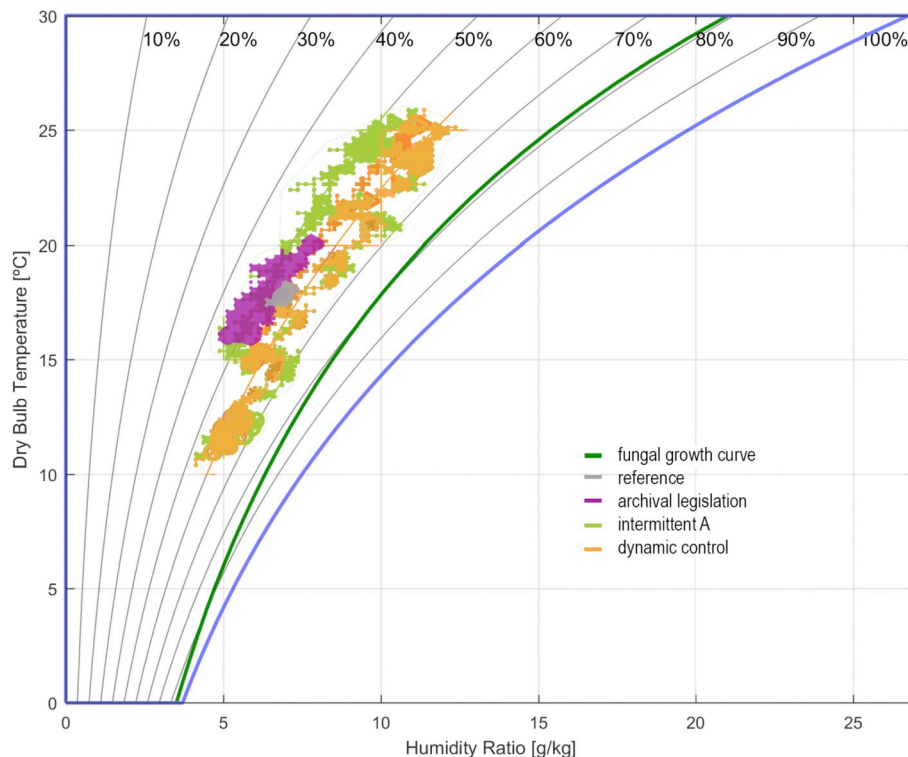


Fig. 12. CEC plot with the indoor climate parameters simulated for the reference, archival legislation, intermittent A and dynamic setpoint strategy.

of the collection. This is endorsed by the specific humidity which increased during the intervention periods.

Vertical stratification measurements show the indoor climate behavior near external walls and near the collection during the intervention periods. The latter results in limited to no gradients in indoor parameters while the indoor climate near external walls show an increase in temperature, and hence, in relative humidity gradients.

Horizontal stratification measurements show the effect of wall orientation and indoor climate behavior during the interventions. This results in small gradients for both temperature and relative humidity in different zones. Considering the building to be relatively airtight and no active air exchange being present, the indoor climate conditions for T and RH are expected to come to equilibrium after a certain amount of time.

HAMBASE proves to be a suitable tool for simulating multi-zone indoor climates and accompanying energy demand. During this study, the energy demand was calculated based on building needs only. The building and its use is modeled into detail. However, more elaborate results might be obtained in combination with an accurate HVAC model. The dehumidification process by deep cooling and reheating could be more accurate. The inclusion of fan energy in the modeled scenarios may influence the current outcome. Previous research showed the impact of fan energy inclusion on the energy demand [12]. An advantage of simulating only building needs is the low computational effort needed for these calculations. With the inclusion of a coupled HVAC model this could result into large computational effort.

HAMBASE calculations result in averaged conditions for each zone. The averaged measurement results show a good agreement with the averaged simulation results, however, it misses some information such as vertical stratification or the effect near (external) walls or collection. This information is presented in temporal and spatial measurement results sections.

The numerical model developed in this study proves to be suitable to determine the effect of different (intermittent or dynamic) setpoint strategies on energy impact and object preservation. Intermittent conditioning and therefore, the needed energy demand, is highly depending on the control strategy during operational hours of the AHU. Dynamic setpoint control provides a set of minimum and maximum requirements based on a sophisticated algorithm developed in Ref. [12]. This algorithm has been adapted in the current study to exclude thermal comfort requirements which are less stringent in archival functions. A future perspective might include intermittent conditioning during dynamic setpoint control when no active conditioning is needed within the setpoint limits. Instead of using recirculation within the T and RH setpoint limits, the AHU could be turned down to yield energy reduction.

During this investigation it became clear that archival requirements are often combined with requirements for exhibited artifacts [4] or are applicable for very specific types of archival collections [5]. Relating T and RH requirements to risk assessment of an archival collection needs further research, e.g. book collections are stored more likely in bulk than single paper sheets. It is of importance to be aware of the difference in possible risk that belongs to the different types of storage solutions. The present study used the lifetime multiplier based upon material properties of a single object.

The main conclusions of this study are as follows:

- The impact of moisture buffering of the collection should be considered in designing climate control strategies for archives and libraries. In this study RH remained stable due to desorption and absorption of moisture under variable T conditions. It is possible to use computational modeling to model the influence of library collection to include moisture buffering of the objects.
- Conditioning in between two limits, i.e. applying a range of permissible T and RH, instead of one strict setpoint, significantly saves

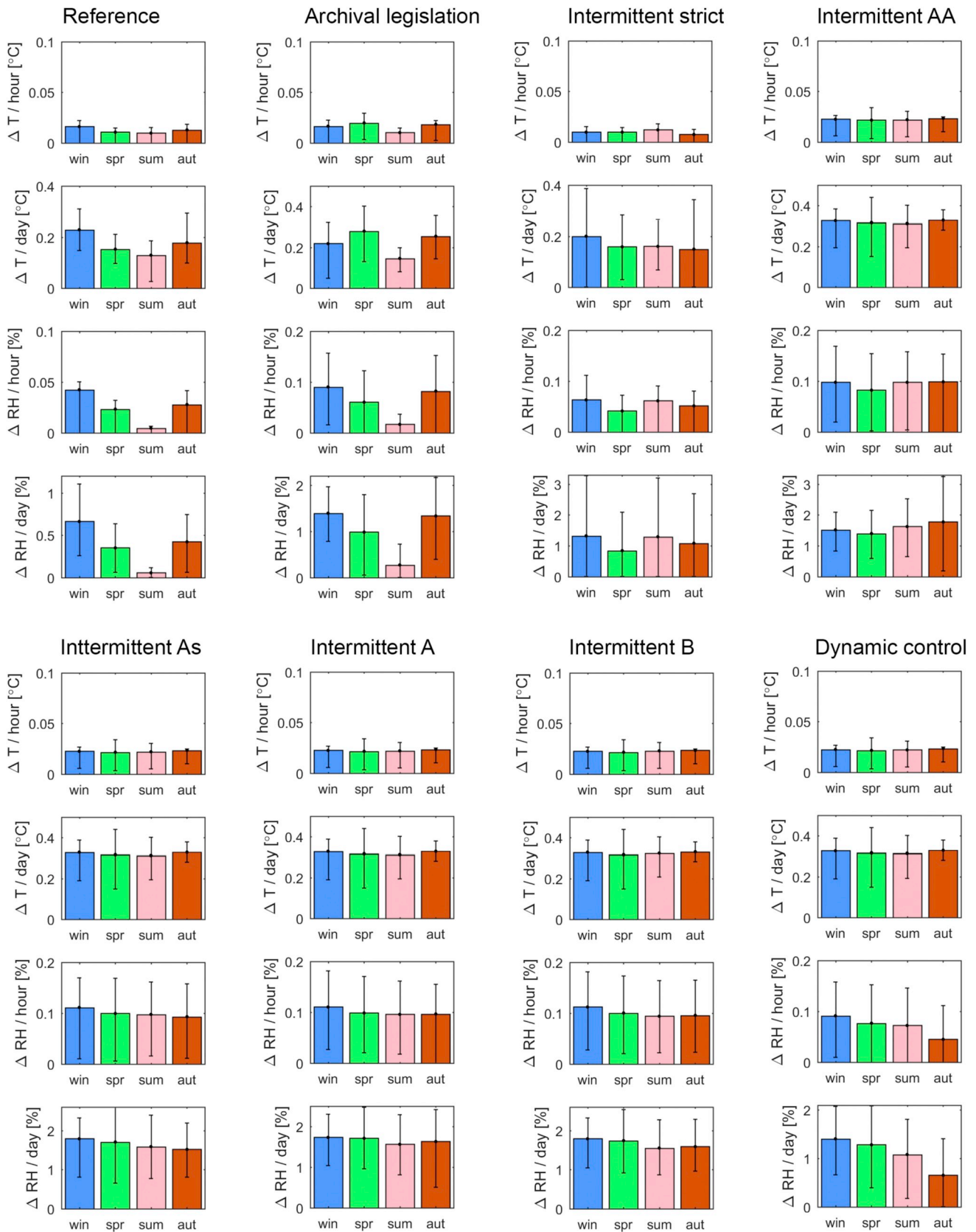


Fig. 13. Histogram plots with the indoor climate parameters per season simulated for all scenarios.

energy: In this study, conditioning according to the Dutch Archival Legislation saved 40% compared to the strict reference case.

- Intermittent conditioning proved to be a viable way to improve

energy efficiency if combined with ranges for T and RH during operational use such as the ASHRAE climate classes used in this study.

- Dynamic setpoint control shows promising results concerning the

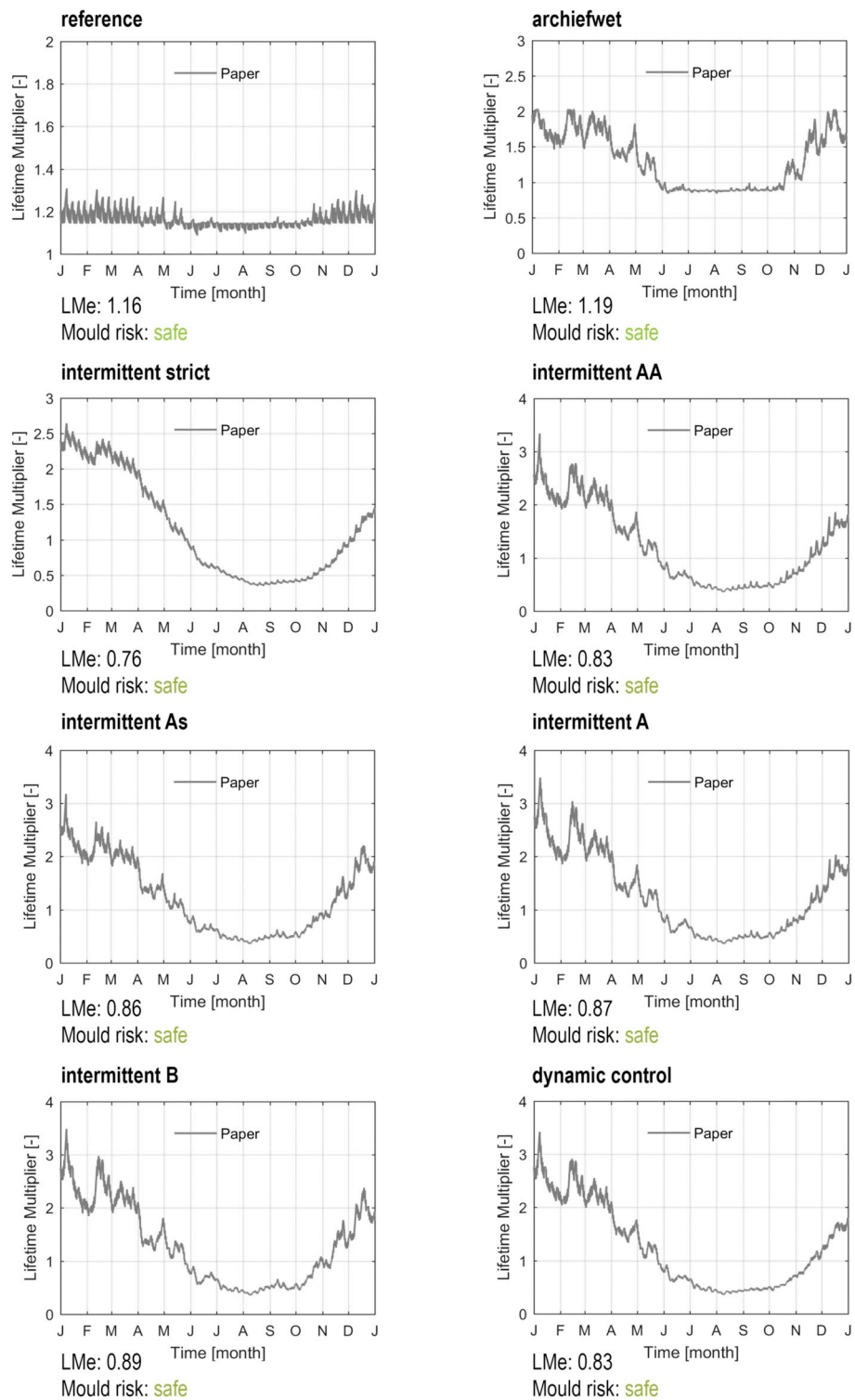


Fig. 14. Mold growth and Lifetime Multiplier for simulated scenarios.

energy efficiency of a library environment. Permissible T and RH ranges based on collection requirements provide more security for library management.

- Reduction in energy consumption is possible for the majority of the tested setpoint strategies. However, collection requirements in terms of object lifetime multiplier should be investigated further. The current lifetime multiplier is based on a single object and might not represent book archival collections as a bulk.

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Appendix A

Based on literature of [27,37], calculations have been performed to receive needed material properties of books in order in HAMBASE to correctly model the impact of a large buffering capacity.

The adsorption isotherm is described based on a Genuchten type curve.

$$w_p(\phi) = w_{sat}(1 + (a \cdot \ln(\phi))^n)^m \quad (3)$$

In which $w_p(\phi)$ [kg/m³] is the specific moisture content of paper related to RH(ϕ) [–], and w_{sat} is the maximum moisture content at $\phi = 1$. a, n and m are parameters defined in Ref. [27]. The parameter a = –5, n = 1.03 and m = 0.9709.

The moisture capacity of paper (ξ_p) can be calculated as follows:

$$\xi_p = \frac{\partial w}{\partial \phi} \quad (4)$$

Another important property is the moisture diffusion resistance factor μ [–]. This factor indicates the relation between the water vapor permeability δ [s] of the material and that of air.

$$\mu_p(\phi) = \frac{1}{a + b \cdot e^{c\phi}} \quad (5)$$

Where a = 0.00167, b = 7.57·10^{–7} and c = 11, parameters mentioned in Ref. [27] for the paper used in this study.

The water vapor permeability of paper δ [s] can be calculated with the following equation:

$$\delta_p = \frac{\delta_a}{\mu_p} \quad (6)$$

Where δ_p is the water vapor permeability of paper, δ_a is the water vapor permeability of air (2.0·10^{–7} at T = 293 K).

To translate the properties of paper to be valid for a book [27], performed experiments that concluded books should be considered as a system of paper layers with air in between. The air layer increases effective vapor permeability. The ratio between paper and air is called the paper fraction (ψ_p). A paper fraction of 75% yields good results for books standing in a book rack according to Derluyn. This is representative for the setup in the case study library.

The water vapor permeability of the book needs to be calculated by using water vapor permeability of paper and air and their weighted fractions.

$$\delta_b = \psi_p \cdot \delta_p + \psi_a \cdot \delta_a \quad (7)$$

From this, the diffusion resistance factor of the book is calculated.

$$\mu_b = \frac{\delta_a}{\delta_b} \quad (8)$$

The moisture capacity of a book can be calculated as follows:

$$\xi_b = \psi_p \cdot \xi_p \quad (9)$$

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