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Evaluation of the indoor environment in a historic museum during the COVID-19 lockdown in Northwest England

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ABSTRACT

Monitoring the quality of the indoor environment is a practice commonly adopted by museums as part of operational risk management. Recorded environmental data are often used to assess the safety of the indoor environment for artefacts, and their suitability for visitors' comfort. Previous studies reported monitoring campaigns assessing the performance of museums and level of compliance with regulatory standards. These analyses were typically conducted in normal circumstances assessing indoor microclimate quality under normal operating procedures. Museum closures during the 2020 pandemic and the global lockdown measures, introduced by governments, presented the heritage sector with an unprecedented situation with empty galleries where collections, in several museums, were held 'dormant' in free-running environments. Assessing the indoor environment in such exceptional circumstances offers a unique insight into the performance of these heritage repositories in other unpredicted situations and potential opportunities for microclimate optimization. This paper reports the results of an extended pre and post-pandemic monitoring that was performed in a historic museum in Northwest England. It contributes to the ongoing universal debate about the application of standardized strict environmental guidelines and the shift towards more contextualized standards in museums in the face of the decline in heritage funding and the pledges for carbon reductions.

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Museums; collection care; COVID-19 lockdown; indoor environment; extended in situ monitoring

Introduction

The correlation between the quality of museum indoor environments and the safety of collection items is well researched in the literature and understood in practice. Museums, as repositories of cultural heritage, are responsible for preserving valuable objects for posterity, by managing risks of degradation caused by the various agents of deterioration. Primary risks to collections include pest infestation, poor unstable thermal environment, extreme light levels and UV exposure, dust pollutants, water ingress, fire, vandalism and theft, inappropriate object handling and other deteriorating issues caused by historic features and the building fabric (Institute of Conservation (ICON), 2020). Implementing feasible measures to preserve collections from the environmental causes of deterioration while satisfying visitors' thermal comfort is complex, and often described among museums' most demanding functions (e.g. Silva et al., 2016). In recent years, the museum conservation mission is further complicated by the necessity to reduce its carbon footprint through the implementation of energy efficiency measures. Museums vary in their funding resources, properties and assets, visitors' numbers and revenue, collection care approaches, status, and in-house conservation expertise. Understandably such variation in resources has resulted in various operational management practices influencing museums' capacity to meet regulatory conservation and comfort demands. Cultural dimensions and geographical variables are also key contributory factors in museum management and care of collections (Agbota et al., 2013). However, the global lockdown restrictions that were introduced as a measure to reduce the spread of the COVID-19 pandemic in 2020 resulted in a rather less customized, less localized situation with museums around the globe necessarily locking their doors and shifting to a different reality. For a certain timescale, and regardless of geography, status, and brand, museum galleries, which are usually brought to life by the flowing visitors, had become completely hollow and abandoned.

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Collections were held, in a number of museums, 'dormant' for a significant period and depending on operating procedures and emergency planning, appliances were either partially turned down diminishing the reliance on mechanical systems or remotely controlled. The stable highly controlled indoor conditions that museums usually strive to create and maintain in compliance with international standards as part of collection care and preventive conservation practices were now replaced by different, and (in cases) free-floating environments. In some museums and with restrictions on access, onsite key workers such as security and facility personnel who are not trained in collections care, were directed to undertake condition checks of collections alongside assisting in implementing necessary preventive actions (e.g. The British Museum, 2020). This unprecedented situation resulted in a unique, natural, and full-scale in situ experimental setting that has never been experienced or envisaged, where new norms had emerged, and long-lasting practices were challenged. Whereas 'special measures' were implemented by heritage organisations to secure the safety of their collections (ICON, 2020), professional concerns over the increasing risk of 'general degradation' due to the reduced levels of preventive monitoring, control, maintenance, and staffing in museums were also voiced during the period. In response, an abundance of online resources was made available by leading heritage organisations offering advice on collection care measures during the lockdown period, followed by post-COVID resources addressing collection conservation issues that may have occurred during the closure. A sample of such resources and their focus is given below.

The UK Heads of Conservation Group (ICON, 2020) produced guidance on 'interim' collections care for museums outlining measures for consideration. The guidance is based on identifying the highest areas of risks across collections (to focus time and resources) and identifying methods to manage the risks. Another concise collection care-focused guidance was also published by the South West Museum Development Programme (2020) including steps and suggested checklists on how to protect objects and keep collections safer during the lockdown by mitigating some of the primary risks to collections (stated above). The Museum of London created an illustrated pocket-salvage guide on saving collections at risk that can be useful in case of an emergency. The National Museum Directors' Council (NMDC, 2021) published good practice guidelines concerning reopening museums to the public. The post-COVID guidance jointly prepared by the UK Heads of Conservation and ICON Collections Care Group was designed particularly to support heritage organisations with limited in-house conservation expertise including suggestions before returning to the site and after reopening. These efforts were further complimented by virtual events, live streaming webinars, sharing practices and providing insights into the implementation of emergency planning, remote collections care and management (e.g. the 'Collection care in lockdown' livestream Q&A panel by the Collection Trust (2020) and the British Museum's member webinar 'Looking after the collection in lockdown' (2020)).

The drive behind these initiatives and other COVID-specific resources was to assist museums in taking the right measures in order to protect and preserve their collections from potential risks, as well as to plan to resolve issues that occurred during the closures after returning to the site and reopening to the public. Among the range of measures recommended and when available, records of indoor environmental monitoring data including those obtained from building control systems during museum closures were named as an essential source of information for inspection after returning to the site (ICON, 2020), as much as being important during the closures as part of museums' remote management strategies. Some of the museums equipped with remote sensing devices for temperature (T) and relative humidity (RH) reported during the shutdown relying heavily on the live data recorded to remotely monitor the quality of the indoor environment by tracing and managing unexpected concerning changes, deviations or odd conditions (e.g. The British Museum, 2020; The Natural History Museum, (Davis, 2020)). Such sole reliance on remote monitoring might have altered how museums normally operate to protect their collections but also left a legacy of evidence on acclimatization of collection items and museum environments in unusual circumstances, a situation that is rarely investigated and assessed, as evidenced by the literature review findings presented in the section below.

This paper investigates the performance of the Salford Museum indoor environment and its collection under alternative conditions during the COVID-19 pandemic closure period in 2020. The paper argues the necessity of applying the strict standardized environmental guidelines that strained museums' resources.

Museum environment in unusual circumstance: an opportunity for microclimatic optimization

The museum environment has been the focus of research for several decades given its direct and multiple influences on museums' mission. Inadequate conditions of the internal museum environment are a primary agent for object deterioration and a cause of visitor's discomfort. A large number of studies investigating the quality of microclimatic conditions in museums has been published through the years providing empirical measurements collected through monitoring or predicted values generated through computation (e.g. Anaf et al., 2013; Camuffo et al., 2001; Camuffo et al., 2002; Ferdyn-Grygier, 2014; Godoi et al., 2013; Kramer et al., 2018; Martinez-Molina et al., 2018; Mishra et al., 2016; Sharif-Askari & Abu-Hijleh, 2018; Zorpas & Skouroupatis, 2016). Most of the analyses reported were concerned with assessing the level of compliance with object preservation limits and human comfort requirements. Consequently, temperature and relative humidity variations were frequently evaluated (Corgnati et al., 2009; Ferdyn-Grygier, 2016) as well as the spread and concentration of gaseous and dust pollutants (Marchetti et al., 2017; Sanchez et al., 2020). Scholars also examined energy optimization scenarios seeking to define efficient setpoint ranges to reduce museums' energy use and/or enhance visitor comfort (Kramer et al., 2015; Kramer et al., 2016; Kramer et al., 2017). A handful of recent studies have also presented risk-based procedures to assess the homogeneity of indoor microclimate quality in museums or the suitability of hygrothermal ranges (temperature and relative humidity values) for object preservation (Litti et al., 2017; Schito & Testi, 2017). Not much has been reported though about the 'suitability' of microclimatic conditions in museum environments and risks of object degradation in unusual circumstances such as museum closures or system failure events. Until the recent health situation and occurrence of the pandemic, museum environment investigations, particularly in suit monitoring, were obviously conducted under normal circumstances (namely, normal management and operational procedures, occupancy and visiting flow patterns) reporting results of microclimatic conditions that were evaluated within normal boundaries. The literature search conducted at the time of writing this article confirms this trend and the focus on normal operational conditions revealing only a few contributions concerning the care of collections and hygrothermal conditions in unusual circumstances. Brimblecombe and Querner (2021) examined changes in insect populations in Austrian museums during the closure period. The focus was, however, on the change in pest activity that usually thrives in damp uncontrolled and abandoned environments, but not on the climate per se. Van Schijndel et al. (2010) simulated the performance of the HVAC system and the indoor climate in a depot in the Netherlands in failure events and explored alternative design options for the improvement of the climate control concept. The study was conducted after detecting a fault in the system that could have caused serious damage to the artefacts. Concerning museum environment in extreme weather events, Huijbregts et al. (2012) investigated the impact of future climate change on the damage potential of museum objects in historic buildings through the application of risk assessment models. Monitoring the microclimatic variations in museums during the exceptional closure periods, as discuss further below, may allow to define additional permissible T and RH variations to those recorded during normal operational times offering opportunities for climate contextualisation and evidence for safe setpoint optimization options.

A 2021 review paper by Elkadi *et al* inspected over 100 studies that were exclusively focused on museum environmental conditions and management published over the last two decades. The authors classified the sample into specific categories including 'empirical' studies presenting the findings of assessing the quality of the indoor environment of museums located in various regions. They pointed out that despite museums' wide efforts to meet internationally recommended environmental guidelines, there is a general struggle to maintain comfort and conservation requirements within the recommended temperature (T) and relative humidity (RH) limits, particularly in historic non-purpose-built museums. Such remarks, which echo other scholars' observations (e.g. Ferdyn-Grygier, 2016; Sciurpi et al., 2015) and the fact that most objects are more resilient to wider environmental limits than those specified may add more credibility to the growing voices of scholars (e.g. Atkinson, 2014; Živković & Džikić, 2015) advocating the need to adopt more contextualized limits based on the understanding of acclimatization of artefacts rather than using 'stringent' international standards as a blanket reference for setting up museum requirements. Lowering the high energy costs that are required for the provision of tight environmental conditions in the face of the decline in museum resources is the other complementary component in the evolving debate on the museum environment and the necessity for adopting pragmatic operational limits. Reducing the carbon footprint of museums by cutting down on energy use was the biggest drive behind the broadening of the T and RH parameters and the original promotion of the Bizot group's 'green protocol' that sparked the entire debate on the museum environment around a decade ago (Bickersteth, 2014). The financial consequences of the recent health crisis and the decrease in revenues have further raised fresh concerns not only about conservation and security measures within the museums sector but most worrying about the evolution of the sector in general and its' long-term financial sustainability (UNESCO, 2021). Museums' financial losses in the first year of the pandemic were between 40% and 60%, compared to 2019, according to UNESCO (2021). Museums are also among the most energy-intensive sectors of the creative sector in England consuming 2019/20 more than one-third of the sector's energy use (Arts Council England, 2022).

While there is a collective view and an agreement within the sector on the importance of reducing the carbon footprint of museums and improving sustainability, there are also fears among some institutions about the risk associated with relaxing the standards on the collections they care for, as a decarbonization measure (Atkinson, 2014). These concerns and the various positions taken by museums worldwide about relaxing the standards are largely attributed to the current state of knowledge, the science and evidence around material properties and their behaviour in different conditions.

The coordinator of the IIC and ICOM-CC working group on museum environment clarifies this aspect of the debate and the need for 'experiential data' to address this gap in research stating:

> 'The science around the effects of broadened environmental parameters on objects is widely criticised as being inconclusive and too based on **experimental** rather **experiential** data to act upon'. Hence 'there is still extensive research to be carried out and evaluated before decisions about the effects of environmental change can be made. While this research is still in progress, there should be respect for the positions being taken by colleagues who are strongly of the view that without sufficient evidence to the contrary, the status quo should remain the standard'. (Bickersteth, 2014, pp. 223–224)

Museum closure period has offered a rare setting to rethink the museum environment and to assess the impact of the change in operation and occupancy on its quality with a natural full-scale experiment.

This study contributes to this line of research on museum environment by offering a unique insight into the performance of a historic museum under the exceptional circumstances that occurred during the lockdown period. The study aims to determine the impact of the change in the museum operation during the closure period on the indoor microclimate quality and the safety of the collection through the application of risk assessment models. The findings could offer opportunities for safe decarbonisation measures through the rationalisation of temperature and relative humidity setpoints in the case study.

Salford museum and art gallery: a brief history

Salford Museum and Art Gallery (SMAG) is a Grade II listed building in Peel Park Salford, Greater Manchester. The legacy of the museum, which opened to the public in 1850 as the Royal Museum and Public Library attributed to its location in Peel Park, the first urban park in the area, and the ethos behind its foundation as an educational site. The establishment of the museum and library was the outcome of the political will, at the time, and the desire to promote 'means of improving popular taste in matters of art' (Mullen, 1899). They were originally contained with a large Georgian classical villa built about the year 1790. The popularity of the museum attracting nearly 1,240 visitors per day in the first few months after opening (Home - Salford Museum & Art Gallery), meant an expansion soon became a necessity. The north wing was first added in 1852, followed five years later by the addition of the south wing (Figure 1(a)). The Langworthy wing (Figure 1(b)) which was named after the former Mayer of Salford and an early supporter of the museum was added in 1878 connecting the earlier wings. A new wing to the east mirroring that of the Langworthy wing was added in the 1930s replacing the mansion house, which was demolished due to safety precautions. The internal courtyard formed by the four wings was filled in in the 1980s, and new mezzanine levels were added enabling the addition of a new store in the basement, toilet facilities on the ground floor and a café. Further alterations to the top-lit galleries, which are described among the earliest examples of their type, took place in the 1980s and 1990s, shuttering over the clerestory windows owing to concerns over the effects of lighting conditions on paintings.

Externally the museum today looks like a unified structure, but the changes implemented over the years have impacted the specificity and the quality of the indoor environment. Since most windows are not functioning and the old ventilation shafts that run down into the basement are insufficient, air does not flow well through the galleries. The lack of daylighting opportunities in the galleries resulted in a sole reliance on artificial lighting, an opposite practice to what was adopted by the museum in the early years. Humidity and temperature are also an issue as radiators in large parts of the building are not static and the heating is either on or off. While the 'objects

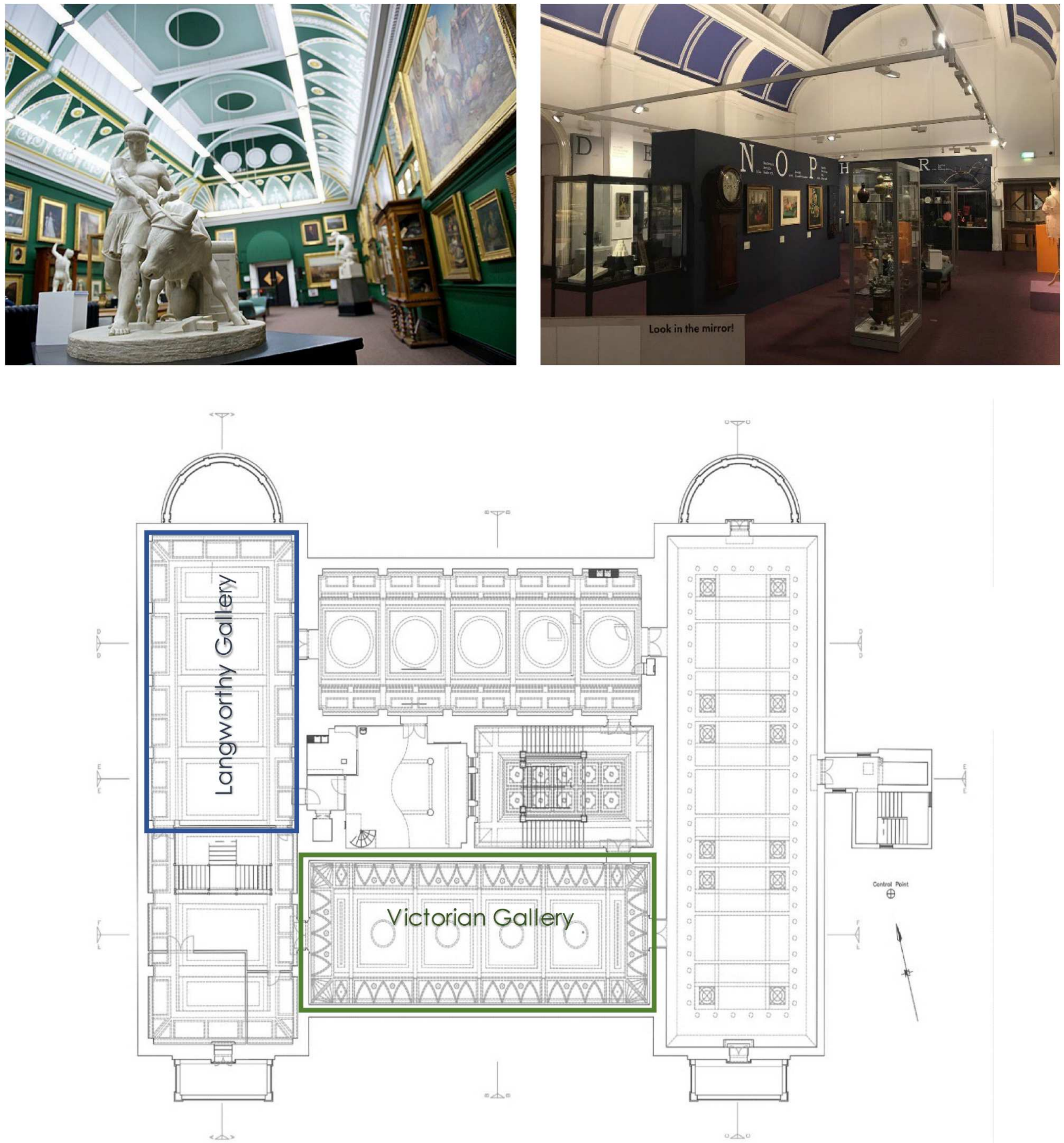

Figure 1. Views of the Victorian or South Gallery (a. upper left) and the Langworthy Gallery (b. upper right), and first floor plan of the museum (*Photograph courtesy of Salford Museum*). For security reasons, no images of the storage areas were included.

seem to work within the parameters, it is more the visitors and the staff who struggle, especially in winter with the different temperatures' according to the museum manager (Horrocks, 2021).

The museum holds a wide collection of paintings, decorative art, social history items, and pottery pieces. The Pilkington company collection and archive held by the museum, which was one of the most international world-class Salford-based suppliers of high-quality pottery in the early twentieth century, are the largest in the UK containing decorative tiles, art pottery, pattern books, notebooks, and company documents. Over 1000 pieces of the artworks exhibited in the Victorian Gallery (Figure 1(a)) and other sections of the museum can be viewed online as part of the repository that was created by Art UK public art collections

(Art UK | Home). In addition to its own collection and permanent exhibition(s), the museum also hosts loan exhibitions of varying duration and themes. It supports local artists by working in partnership with art organisations in the region and beyond on curating temporary exhibitions as well as displaying outstanding pieces by L.S. Lowry and other prestigious artists. Some of the measures undertaken by the museum to allow more opportunities for loan exhibitions included installing a new lighting system with a diming control at the Langworthy Gallery and using portable humidifiers to bring the humidity to a more stable condition (Goodwin, 2018).

During the pandemic, the museum went through various phases of closures and opening with the majority of the staff were furloughed during the first lockdown (March 2020) following the restrictions imposed in the Greater Manchester Area. Regular check visits to the site were carried out on a weekly basis when the restrictions eased. More information about the museum operation is given in the following sections.

Methodology

During the time of lockdown in the United Kingdom, Salford Museum was largely uninhabited and the indoor environmental controls on their oil-fired boiler were adjusted to only protect from frost in order to conserve fuel which would be impossible to replenish under lockdown conditions. Museum staff also visited the museum as regularly as restrictions would allow to ensure the collection and the building itself were not visibly deteriorating and were not subject to accidental damage. The museum was closed from 21/03/2020 and reopened after lockdown on 19/07/2021. Remote environmental monitoring was already underway before the first lockdown recording a range of environmental parameters in sections of the museum including motion, air velocity, light levels, particulates and CO_2. The monitoring campaign was carried out using wireless sensors transmitting through local gateways the recorded data to a secure online monitoring platform/system with a time-step of 15 min. The accuracy of the sensors employed to monitor the hygrothermal performance of the museum (temperature and relative humidity) was +/- 0.5°C and +/- 2%, respectively, according to the manufacturer (Wireless sensors).

The lockdown situation provided, as earlier stated, a natural experiment to determine whether a collection contained in a heritage building provides a safe environment for artefacts without expensive and impactful climate controls. Figure 2 shows the interior and exterior temperatures and relative humidity before and after lockdown. Noticeable changes are a decrease in overall temperature despite the outdoor temperature rising as well as a reduction in diurnal changes as climate control systems are removed. Temperatures also slightly lag changes in the outdoor temperature, and are moderated by the controlling force of the building's fabric and thermal mass. Similarly, relative humidity shows a reduction in diurnal amplitude but a longer-term drift largely driven by temperature changes.

This study compares the museum's performance in protecting its artefacts over two periods:

- 15th July 2020 to 28th June 2021 when it was closed. This is shown as 'uncontrolled' in the results.
- 15th July 2021 to 28th June 2022 when the museum was opening and climate control was in place, shown as 'controlled' in the results.

Over the study periods the underground Ethno store experienced a mean of 16.3°C and a standard deviation (SD) of 1.3°C under uncontrolled conditions and a similar, but more varying 16.3°C, SD 1.6°C under controlled conditions. Mean relative humidity was 56.2% with SD of 9.6% under uncontrolled conditions and 59.8%, SD of 7.1% under controlled. The ground-floor Langworthy Gallery was slightly cooler over lockdown with a mean temperature of 17.7°C and SD of 2.5°C compared with 18.4°C and SD of 2.5°C under controlled conditions. A mean RH of 48% and SD of 5% under uncontrolled conditions and 56% SD 3% under controlled conditions. It should be noted, however, that the small changes in SD in both temperature and RH between the uncontrolled and controlled periods do not properly describe the changes in the spaces as short-term fluctuations between controlled limits were replaced by longer-term changes as shown in Figure 2.

Figure 3 shows the study periods involved along with data from light, CO_2, and motion monitoring showing the changes in occupancy as well as a time series of relative humidity, indoor and outdoor and temperatures.

Environmentally sensitive items made of organic hygroscopic materials, cellulose or metal react to T and RH, which can cause changes in the moisture content and the heat experienced by an object, leading to various mechanical, biological and/or chemical deterioration processes. These processes characterized by differences in temperature and/or relative humidity experienced by the multiple layers of an object_ can be identified from materials' response using a range of methods. Hence, measured environmental parameters were used in calculations to derive artefact-centric measures of mould growth potential, mechanical

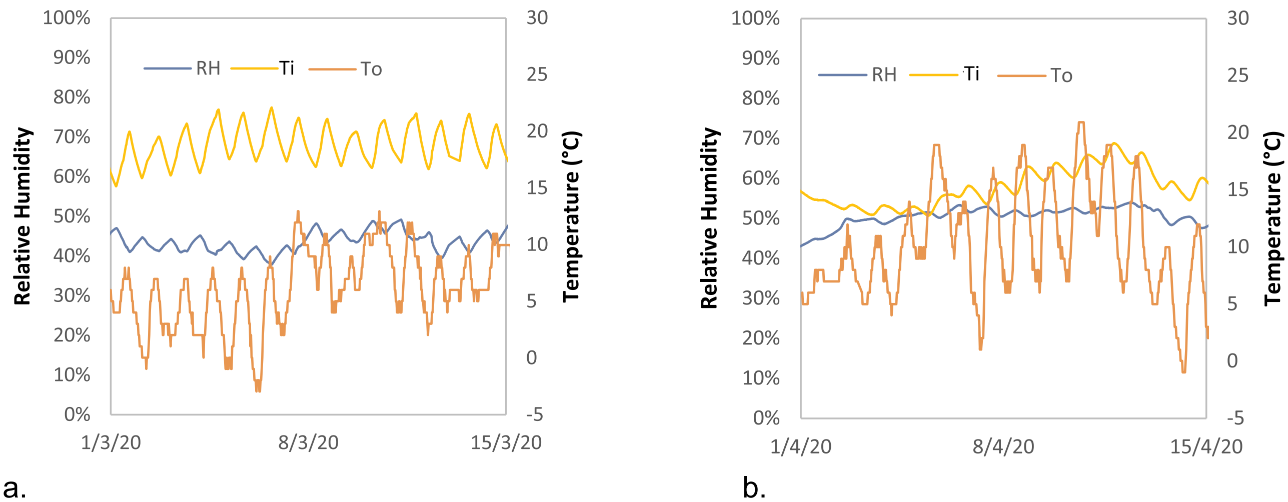

Figure 2. Relative humidity (RH), indoor temperature (Ti) and outdoor temperature (To) readings soon before and after lockdown. (a). controlled environment just before lockdown; (b). uncontrolled environment soon after lockdown.

damage, and chemical degradation, primarily due to changes in temperature and relative humidity, as described in the following sections. Similar metrics or what is referred to in the literature as 'risk assessment models' were used by Silva and Henriques (2015), Silva et al. (2016) and Schito and Testi (2017) and are largely derived from the work of Martens (2012) with some updated source material for underlying data. The following sections elaborate on the application of these functions in quantifying the risk of biological, chemical, and mechanical damages to the collection at the museum.

A limitation of lockdown was that it was not possible to maintain equipment, as access to the museum was restricted along with movement around the city. This was particularly true in Manchester as it was an early suffer from the 'second wave' of infection. Of course, it was this very restriction, along with the maintenance requirements of the heating system that allowed for the comparison in the first place. As a result, there is some data loss from 28th September to 21st October in the store and 22nd July to 21st October in 2020 and for both spaces from 19th January to 1st March in 2022. It should be noted, however, that the building is free-running in the summer and these periods are removed from the analysis in both controlled and uncontrolled scenarios.

Mould growth

A number of authors (Costanzo et al., 2021; Martens, 2012; Schito & Testi, 2017; Silva & Henriques, 2015, 2021) performing risk assessments on the indoor environment of museums have used the isopleth method of Sedlbauer (2001, 2002), which is widely cited in the literature including relevant Standards (BSI, 2012, 2017; 2018; 2018). A conservative approach was used in this work with a safe zone defined which corresponded with the region below the lowest isopleth for spore germination. The region boundary was fitted to a quadratic equation corresponding to $RH = 0.03T^2 - 1.78T + 98$, which is in-keeping with the form of other Isohyet models described in Vereecken and Roels (2012) and Hens (1999).

Chemical degradation

The Lifetime Multiplier (LM) developed using the Arrhenius equation by Michalski (2002) compares the potential for chemical degradation to a 'standard' environment of 20 °C and 50% RH. Martens (2012) developed the following formula from Michalski's work:

$$LM_x = \left(\frac{50\%}{RH_x}\right)^{1.3} e^{\frac{E_A}{R}\left(\frac{1}{T_x} - \frac{1}{293}\right)} \tag{1}$$

where LM_x is the lifetime multiplier for the time-step, RH_x is the relative humidity experienced by the object at the time-step (%), E_A is the activation energy (J/mol), R is the gas constant (8.314 J/mol K), T_x is the temperature at the time-step (K). The method incorporates an arithmetic running mean of the last 30 days for RH and 24 h for temperature as specified in the methodology for calculating the Image Permanence Institute's Time-Weighted Preservation Index (TWPI) (Nishimura, 2011; Reilly et al., 1995). The LM has been graphed as a time series for 2 values of E_A, 70 kJ/mol which is used for varnish yellowing and 100 kJ/mol

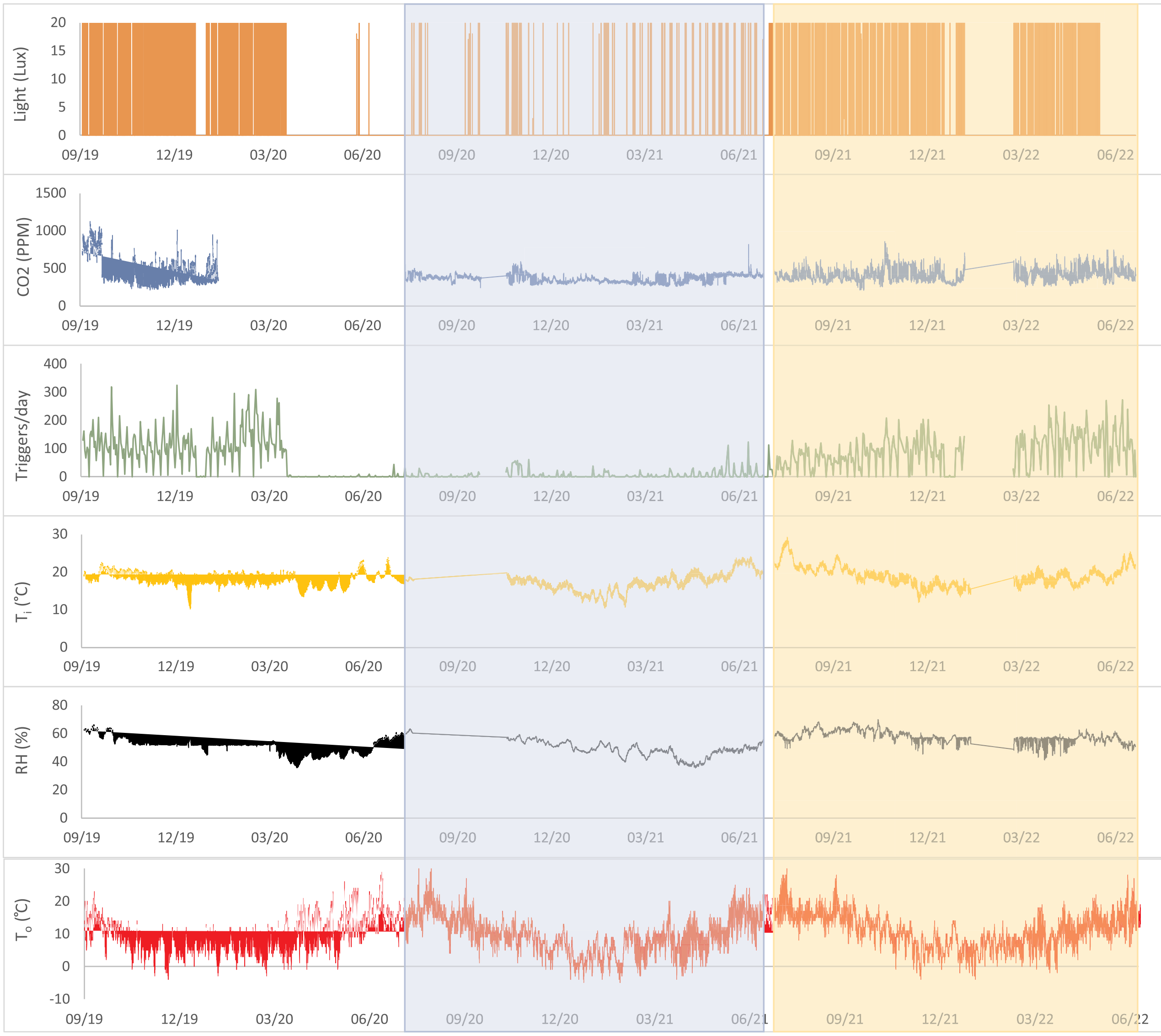

Figure 3. Measured data from the Victoria Gallery of the Salford Museum. The blue region is the closed, relatively uncontrolled section during lockdown, the orange is when the museum is open and controlled.

which is appropriate for the degradation of cellulose materials such as paper.

As chemical degradation is cumulative, the overall LM experienced by an artefact is a useful measure. It can be achieved by finding the reciprocal of the mean of the reciprocal of each value of LM which is in keeping with the calculation of the TWPI (Reilly et al., 1995).

Mechanical damage due to changes in humidity

Mecklenburg et al. (1998) developed a method to assess the potential for mechanical damage to wooden objects due to hygrothermal changes which resulted in charts with boundaries defining reversible elastic and irreversible plastic behaviour and consequent allowable fluctuation in relative humidity of the materials considered. These charts have subsequently been used by a wide range of authors in modelling and risk-assessing museum environments (Coelho & Henriques, 2021; Costanzo et al., 2021; Huerto-Cardenas et al., 2021; Huijbregts et al., 2012; Litti et al., 2017; Martens, 2012; Schito & Testi, 2017; Silva & Henriques, 2015, 2021). Bratasz (2013) subsequently superimposed the graphs from a range of artefacts made from Japanese cypress (Bratasz et al., 2008), lime wood (Jakieła et al., 2008) and cottonwood (Mecklenburg et al., 1998) on common axes providing the potential to define a safe zone for a number of woods with varying properties. Figure 4 shows the defined safe zone within Bratasz's figure.

Martens further developed this idea by considering the moisture gradient between the surface and deeper parts of the material acting against each other. As

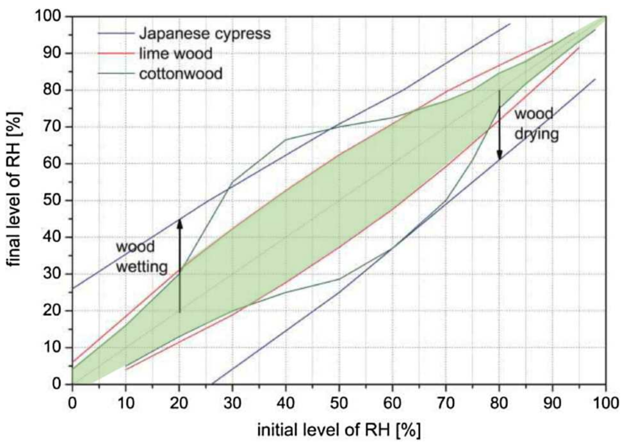

Figure 4. Japanese cypress, lime wood & cottonwood mechanical damage graphs on common axes (Bratasz, 2013) with proposed 'safe' region in green added by the authors.

moisture takes time to penetrate into an object, there will be differential expansion and contraction within it. The form may be accounted for by considering different response times of larger and smaller objects in determining the value of the 'final level of RH'. To calculate the surface and full response, Martens (2012) developed a simplification of a first-order function when the time-step is small compared to the response time of the form:

$$RH_{response,i} = \frac{RH_{response,i-1} + \dfrac{RH_i}{n/3}}{1 + \dfrac{1}{n/3}} \tag{2}$$

where $RH_{response,i}$ is the relative humidity experienced by the artefact at the timestep, $RH_{response,i-1}$ is the relative humidity experienced by the artefact at the previous time-step, RH_i is the relative humidity of the air at the time-step i and n is the number of time-steps in the response time for the artefact. Martens also tabulates a number of response times for a range of artefacts based on a typical depth of penetration in the half responses from the ASHRAE handbook (ASHRAE, 2015) and other sources as shown in Table 1, which also includes the number of readings the data loggers in Salford Museum took within the response time.

Results and discussion

Surprisingly, the controlled environment provides the greatest range of temperature for both spaces with temperatures ranging from 12.7°C to 21.6°C (a range of 8.9°C) in the Ethno objects store under controlled conditions and 11.6°C–19.6°C (8.0°C) when uncontrolled, with measurements of the Langworthy Gallery ranging from 12.0°C to 28.9°C (16.9°C) and 11.8°C–24.2°C (12.4°C). The high temperatures, however, form a short-lived spike in otherwise more moderate conditions. Turning to relative humidity, the uncontrolled spaces show an increased range with the store experiencing a RH of 44%–72% (a range of 28%) under controlled conditions and 41% to 75% (34%) under uncontrolled. While the gallery ranged from 41% to 64% (23%) and 36% – 63% (28%).

Comparing to standards shows mixed results with the expected very few readings within the strict '50/70' rule that stipulates 70°F ± 2°F (equivalent to 21°C ± 1°C) & 50% RH ±5% that has formed the mainstay of Museum recommendations (Elkadi et al., 2021) with the gallery only complying 7.0% of the time when controlled and 6.8% when uncontrolled and temperatures in the store so low that it never complies. The more relaxed Bizot/NMDC recommendations of 16–25°C & 40–60% RH (Bizot Group, 2015; NMDC, 2008) show some important differences with 76.4% of readings complying in the gallery when controlled and fewer readings (62.1%) complying when uncontrolled. The reverse is true of the cooler store where 11.8% of readings comply when controlled and 35.1% when uncontrolled. Beyond simple prescriptive standards, the three metrics explained above were used to assess the quality of the indoor environment and the potential damage to the artefacts in the two zones.

Biological damage

Figures 5(a and b) show the frequency of relative humidity (RH) and temperature (T) measurements as coloured heat maps on the left-hand side with red indicating many readings with that combination of temperature and humidity and violet, very few readings.

Table 1. Response times calculated by Martens (2012).

Object	Relevant response	Response time	Reference (used by Martens)	Salford Museum logging time steps in response time
Paper	Full response of single sheet	'Minutes'	(Michalski, 1993)	<1
Panel painting	Surface response just under oil paint	4.3 days	(ASHRAE, 2015)	413
	Full response of entire panel	26 days	(ASHRAE, 2015)	2,496
Wooden sculpture	Surface response	10 h	(ASHRAE, 2015)	40
	Sub-surface response causing maximum stresses	15 days	(Vici et al., 2006)	1,440

Note: Martens used a 2011 edition of ASHRAE, but the relevant data is unchanged in the 2015 edition.

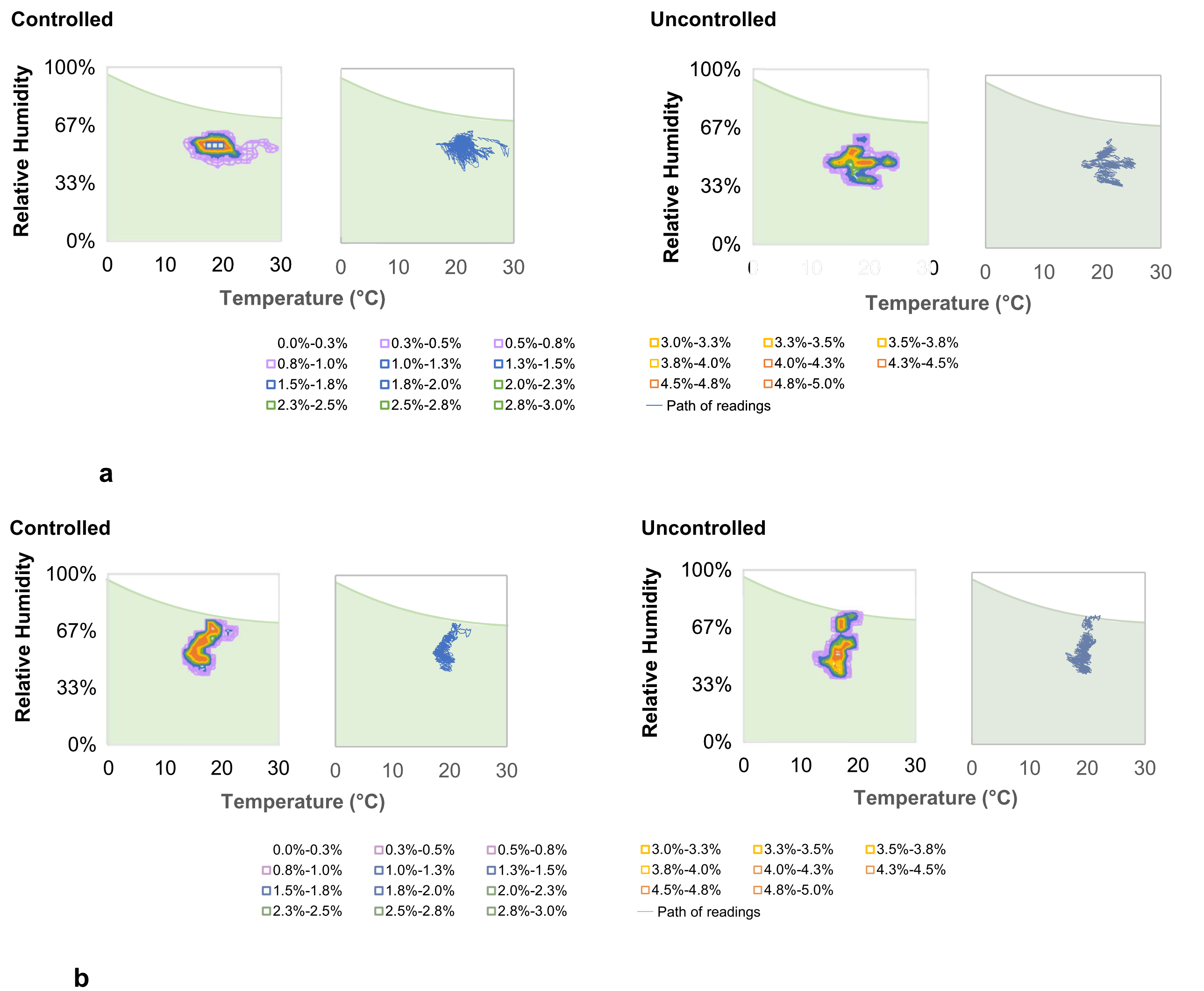

Figure 5. **(a)**: Potential for mould growth for artefacts in Langworthy Gallery. **(b)**: Potential for mould growth for artefacts in the Ethno Objects Store.

along with the pathway of readings overtime on the right. The green area is the safe region where mould cannot germinate. Outside of this region germination can take place with faster germination associated with greater deviation from the safe zone. Neither period shows any chance of mould growth in the gallery with all measurements well within the safe zone. For the store, there is a very short period of 16 h outside the safe zone in a region corresponding to a germination time of 32 days (Sedlbauer, 2002). The heat maps show a slightly closer approach to the germination zone for more readings than under controlled conditions which is what should be expected.

It is also notable that both controlled and uncontrolled conditions demonstrate conditions less conducive to mould growth than has been found in other studies such as the churches in Mediterranean climates studied by Costanzo et al. (2021) and Silva and Henriques (2015) and also safer than museums simulated in Belgium and Netherlands by Huijbregts et al. (2012). This is a slightly surprising result as Manchester is a location famed for its damp and rainy conditions, but shows that passive design is very capable of maintaining mould-free conditions in a museum. It is also worth noting that the gallery experienced an overall drop in relative humidity which gives some support to reports that visitors make significant contributions to relative humidity in display spaces (British Museum, 2020) and also supports simulations by Schito and Testi (2017), which simulate the effects of HVAC systems being shut down overnight with resultant reductions in RH.

Mechanical damage

Figures 6 (a and b) & 6 (a and b) show heat maps and the path of changes in relative humidity at the surface and full penetration into artefacts in Langworthy Gallery

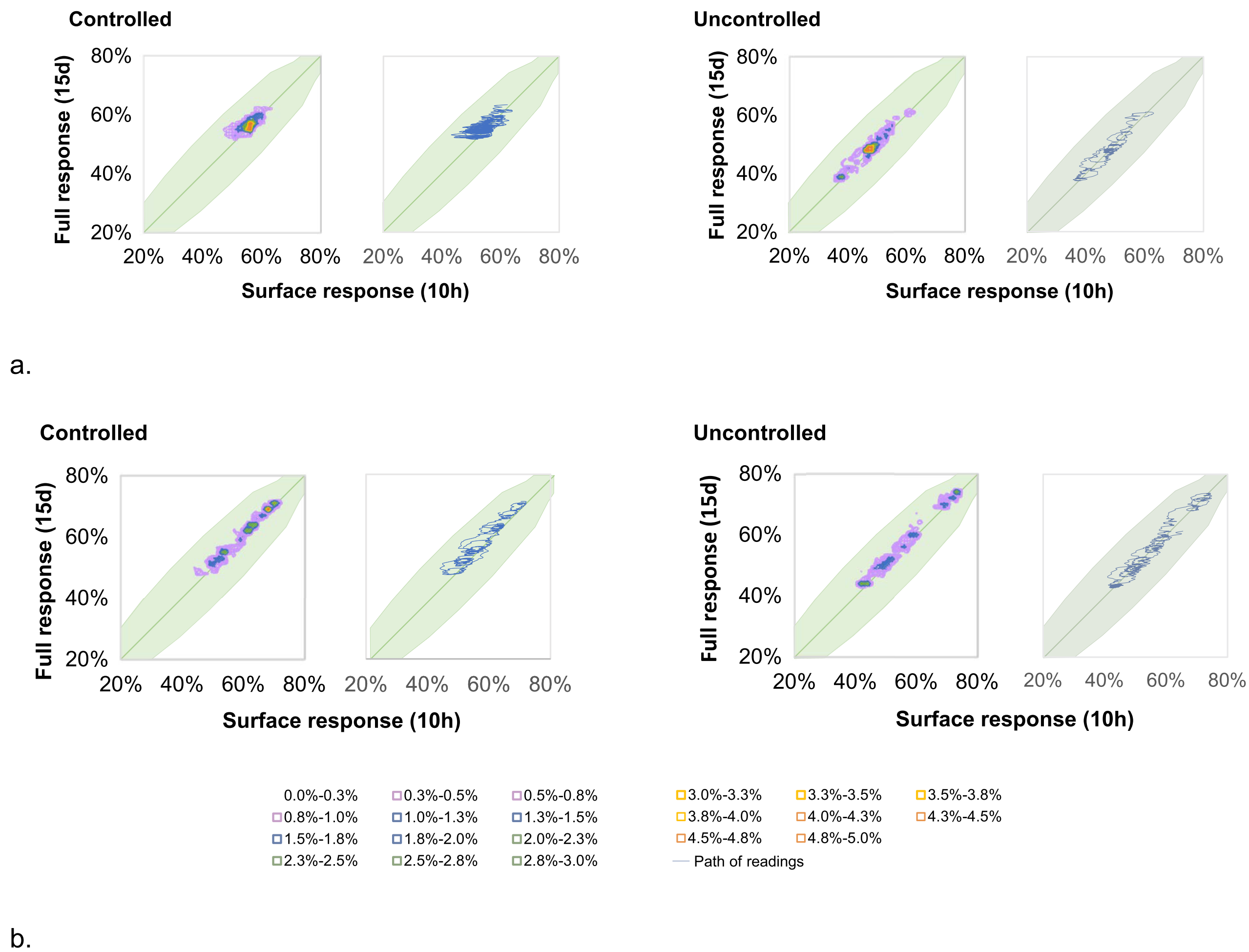

Figure 6. Penetration of humidity into wooden sculptures. (a). Langworthy gallery; (b). Ethno objects store.

and the Ethno objects store. The green region shows an area where only elastic deformation takes place, while the region outside this will result in plastic deformation which is not reversible. Both sculptures and painted boards are well within the safe zones for all readings and so the artefacts can be considered safe from mechanical damage under both controlled and uncontrolled conditions. In the gallery, the effects of the wider range of RH experienced by the artefacts can clearly be seen in the graphs with uncontrolled graphs showing a larger range of values across both surface and full responses, however, it is also apparent that the speed of change is slow enough that these changes are experienced by the objects as a whole rather than simply on the surface which would result in differential expansion and potential damage such as surface cracking or delamination. This is particularly notable in the Langworthy Gallery where under controlled conditions, there are closer approaches to the edges of the safe zone because of diurnal changes in humidity due to factors such as cycling of environmental controls and comings-and-goings of visitors. Comparisons with similar results from the literature, again show generally slightly better control than in other studies using these metrics (Huijbregts et al., 2012; Silva & Henriques, 2015), though Schito and Testi (2017) found similar levels of deformation in their simulations of a controlled space in Pisa. Figure 7.

More precise insight than simple pass-fail can be gained from these measures as perfectly balanced humidity will result in no possible damage from differential expansion of the artefact. It is, therefore possible to further compare the two regimes by investigating the coefficient of determination (r^2) according to a unit gradient line passing through the midpoint of the graph as shown by the green line drawn from the bottom left to the top right in the figures. The r^2 for sculptures under controlled conditions is 0.57 for the gallery and 0.94 for the store, while uncontrolled conditions have a better fit with an r^2 of 0.86 and 0.96 respectively indicating that counter to expectation, controlled conditions result in slightly more elastic deformation. Similarly, for panel painting, the r^2 for controlled

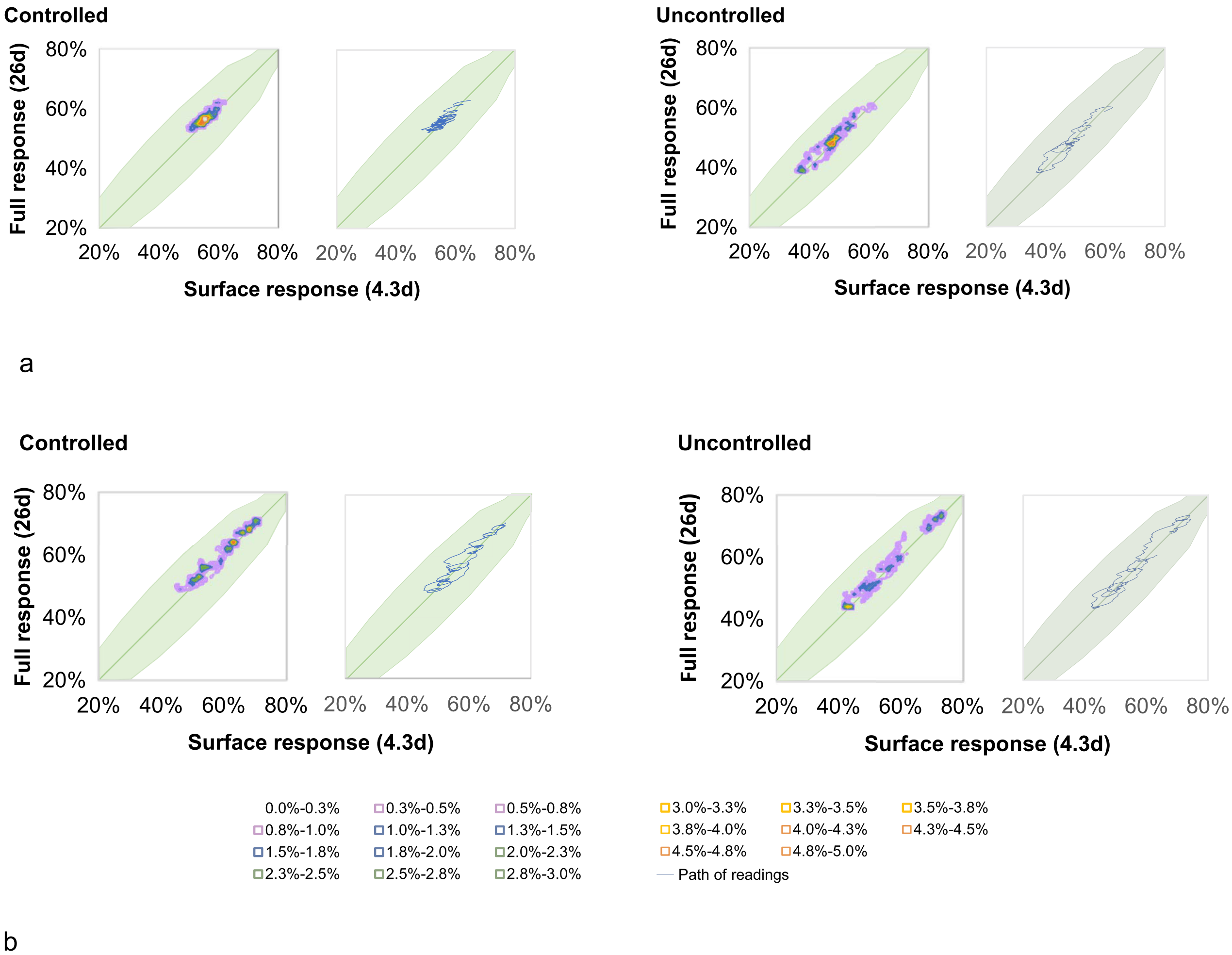

Figure 7. Penetration of humidity into panel paintings. (a). Langworthy gallery; (b). Ethno objects store.

environments is 0.79 and 0.95, while the uncontrolled environments deviate from unity with a slightly better r^2 of 0.86 and 0.96. While the general recommendation (Bratasz, 2012; Mecklenburg et al., 1998; Michalski, 2016) is that artefacts are safe, so long as they are kept within their elastic range, this result may indicate a potential for adopting a more cautionary approach, particularly for critical artefacts which are liable to damage by fatigue. As the relevant dimensional changes take place over days and weeks, this, more cautious approach is, a function of rates of change rather than absolute values, so it is not solved by simply specifying a smaller range for the deviation in RH and T or even changes in short time periods such as 24 h such as is done in the Bizot Green Protocol (Bizot Group, 2015) as this may well be counterproductive with the potential for faster changes brought about by environmental controls creating more issues than the slower changes created by natural environments as has been suggested by Camuffo et al. (2001, 2002) and Ferdyn-Grygier (2016).

Chemical degradation

The lifetime multiplier was calculated over the two study periods. The resulting graphs are shown in Figures 8 and 9. The graphs themselves are quite similar, though the controlled environment shows a dip in early July due to an elevated temperature. A Time-Weighted Preservation Index (TWPI) was also calculated for each period by just considering the cumulation of LM over each study period. The TWPI of the controlled environment was calculated as 1.04 for 100 kJ/mol activation energy and 1.09 for 70 kJ/mol activation energy for the Langworthy Gallery and 1.20 and 1.38 respectively for the Ethno objects store indicating that these spaces are generally better than the usual controlled conditions for conservation against chemical degradation. They are, however, somewhat worse than the uncontrolled environment where the TWPI was 1.20 and 1.29 for Langworthy and 1.28 and 1.49 for Ethno, likely due to the lower temperatures experienced by the collection

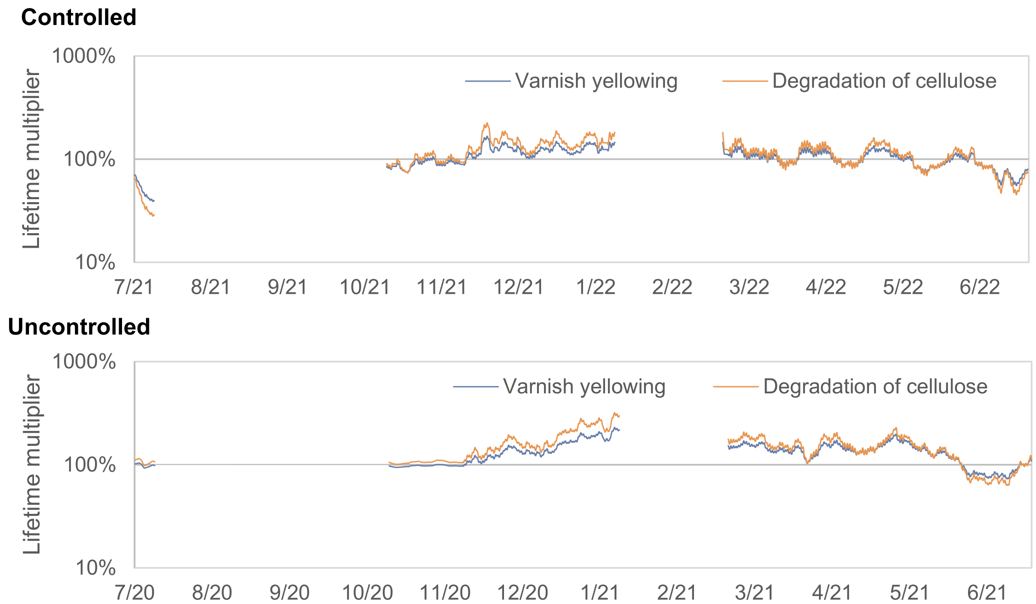

Figure 8. Lifetime multiplier of artefacts stored in Langworthy Gallery. A higher number indicates longer life. Zero indicates a lifetime under 'standard' conditions of 20 °C and 50% RH.

under uncontrolled conditions and shown by the higher lifetime multipliers during the winter months.

Taken together these results show that artefacts can be kept safe without closely specified environmental controls. The replacement of short-duration fluctuations brought about by daily control adjustments with longer-term, slower fluctuations has led to very similar mechanical damage expectations despite the increased magnitude of these fluctuations with conditions within safe limits at all times and, in fact, closer conformity to equilibrium under uncontrolled conditions due to the slower speed of change. Requirements for keeping artefacts below certain thresholds for controlling biological activity have been met passively through the hygroscopic action of the building fabric regulating relative humidity and thermal mass regulating temperature. The overall temperature reduction in the building has had a positive effect on chemical degradation control, however, some of the resultant temperatures are unlikely to be popular with visitors in the colder months.

It should also be noted, that while energy use was not a focus of this study, Salford Museum saved a

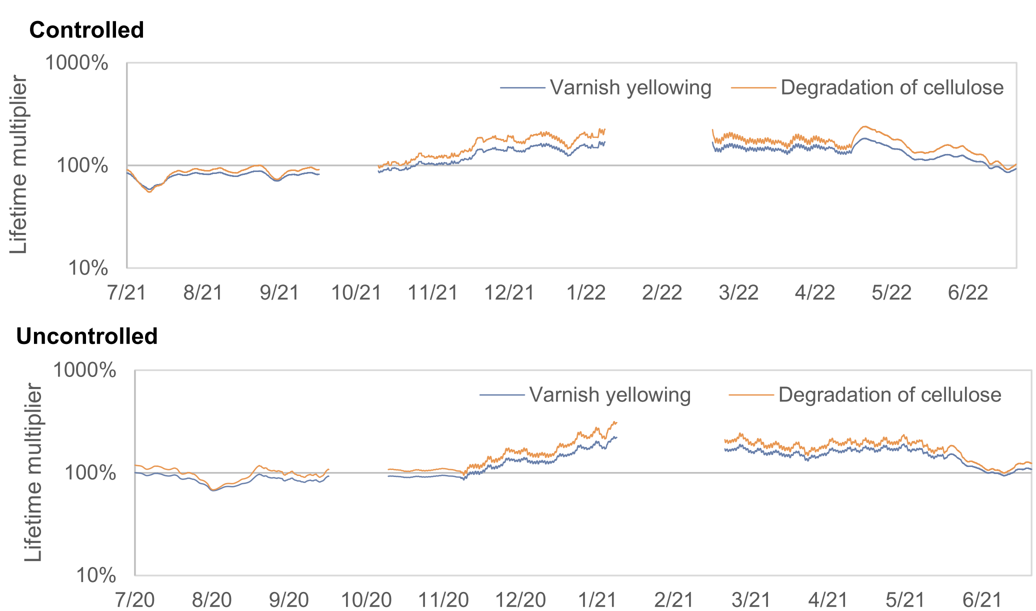

Figure 9. Lifetime multiplier of artefacts stored in the Ethno Objects Store.

considerable amount of oil over this period with consequent cost reduction and reduction in direct greenhouse gas emissions from their boiler. This supports the work of Kramer et.al (2015, 2016) who did simulations and measurements of a museum in Amsterdam and showed savings of up to 77%. Given the promising results over lockdown, it is possible for greater reductions in Salford depending on the needs for visitor comfort.

Conclusions

Following the ICOM Environmental Guidelines ICOM-CC and IIC Declaration in 2015 (ICOM, 2023), museums have been seeking to reduce their carbon footprint and environmental impact to mitigate climate change by reducing their energy use and examining alternative renewable energy sources. While there is a recognition that Temperature and Relative Humidity parameters for preservation of collections differ according to their material, construction and condition, relatively strict guidelines are believed to be generally acceptable for most objects. More recently, the energy crisis has led museums to rethink their energy use and indoor environments. Monitoring of museums' indoor environments to maintain temperature and humidity within the limits of those guidelines usually takes place under normal operating procedures and during normal opening hours and occupancy patterns. The COVID-19 pandemic and the long period of closure of museums in 2020 offer a unique opportunity to investigate the performance of museums' collections under alternative conditions. The result of this investigation not only provides an insight into possible relaxation of the relatively strict regulations but also the impact of other unpredicted situations such as in the case of HVAC system failure.

This paper examines data collected in the Langworthy Gallery and the Ethno store at Salford Museum during and after the lockdown period between March and September 2020 and March to September 2021 when the museum was opening, and climate control was in place. Data related to temperature and relative humidity were used in analysis to derive artefact-centric measures of mould growth potential, mechanical damage, and chemical degradation. Analysis of heat maps of the frequency of readings taken during the two identified periods shows no chance of growth in the Langworthy Gallery. It is important to note that the gallery is situated on the upper floor of the poor air-tight Victorian building enclosure. Analysis of the uncontrolled environment in the store, however, shows a slightly closer encroachment to the germination zone during closure period than under controlled conditions. Such proximity to the germination zone however occurred for a short period of time and paused no risk to the collection. Analysis of data collected during the lockdown closure period doesn't make much difference to the store. This is possibly due to the underground location and infrequent visitation even when the museum is open.

The paper also examined the possible penetration of humidity into artefacts which may result in differential expansion of the material, particularly in wooden objects. The analysis shows that controlled conditions, without impact of visitors, have a better fit indicating that closure conditions could result in slightly less elastic deformation. At both the Langworthy Gallery and the Ethno store, readings fall within the safe range and no possible threat to the collections is indicated.

Analysis of Chemical Degradation indicates that graphs representing the two periods are quite similar, despite the controlled environment showing a dip in early July due to an elevated temperature.

The comparative analysis, of data collected during normal museum operations and the closure time during the COVID-19 pandemic, gives no indication that the collection was at risk at any time. In the context of Salford Museum, incorporated into a heritage building, the data shows possible relaxation of the regulations beyond what is currently considered as a safe setting of temperature and relative humidity. The paper provides measured data to argue for more contextual applications of the current regulations.

The results show that during closure time 'dormant' indoor environmental conditions remained generally within acceptable levels for the examined artefacts. The relatively lower environmental setting did not pose risks to the museum exhibits. Such results support the current debate on the need to re-visit the strict environmental guidelines. The results also argue for the need for more contextualized rather than generic environmental guidelines for indoor settings in museums. Such considerations would have a major impact on energy requirements and on lowering carbon footprints for museums around the World.

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