CLIMATE FOR COLLECTIONS
STANDARDS AND UNCERTAINTIES

Edited by Jonathan Ashley-Smith, Andreas Burmester and Melanie Eibl

Postprints of the Munich Climate Conference
7 to 9 November 2012

CLIMATE FOR COLLECTIONS
STANDARDS AND UNCERTAINTIES
2013

Edited by Jonathan Ashley-Smith, Andreas Burmester and Melanie Eibl
Munich 2013

CLIMATE FOR COLLECTIONS
STANDARDS AND UNCERTAINTIES

Front cover illustration: Joachim d'Alencé: Traittez des Barométres, Thermométres et Notiométres ou Hygrométres, Amsterdam 1707

Contents

Foreword

The debate about environmental standards for museum collections has by no means been resolved. Climate change, ever increasing energy bills, the complexity of air-conditioning systems, the feasibility of alternative climate control strategies and the real effects of inappropriate indoor environments on collections pose major questions for conservation professionals.

The papers in this volume investigate what is known and what is not known about suitable environmental conditions for cultural heritage collections. CLIMATE FOR COLLECTIONS STANDARDS AND UNCERTAINTIES presents the most significant recent research on the subject, informed by a major international conference, held at the Pinakothek der Moderne in Munich from 7 to 9 November 2012 on the occasion of the 75th anniversary of the Doerner Institut.

The global imperative to save energy and reduce our carbon footprint is evident. Museums and other cultural institutions are deeply implicated in these concerns as major consumers of energy, particularly those housed in modern buildings. The demand for a better understanding of the interactions between cultural heritage collections and the climate is pressing. The EU-funded research project Climate for Culture is currently investigating the influence of current and future climate change on cultural heritage objects. Serious concerns have been raised in the conservation community at recent extensions of the range of acceptable climate criteria for both permanent exhibitions and loans, and new theories such as the 'proofed fluctuation concept' are much discussed.

CLIMATE FOR COLLECTIONS STANDARDS AND UNCERTAINTIES addresses these issues. By adopting broad definitions of both 'climate' and 'collection', the subject has been expanded beyond the concerns of previous conferences such as 'Museum Microclimates' (Copenhagen 2007) and recent discussions such as 'The plus/minus dilemma' (IIC/AIC 2010). To ensure these questions are addressed in depth, the topics of climate change and sustainability have been introduced. The current volume contains 35 contributions and some 20 posters are available for download from www.doernerinstitut.de.

This publication was kindly supported by the EU-funded research project Climate for Culture and the Doerner Institut. The editors would like to thank the many authors, as well as May Cassar and Rebecca Bennett (London), Joachim Huber (Winterthur), Roman Kozłowski (Krakow), Poul Klenz Larsen (Copenhagen), Renate Poggendorf (Verband der Restauratoren e. V. Bonn), as well as Ruth Krauß and Julia Arzberger (Munich) for their grand support.

Jonathan Ashley-Smith
Andreas Burmester
Melanie Eibl

Allowable microclimatic variations in museums and historic buildings: reviewing the guidelines

Łukasz Bratasz

Abstract

Environmental standards for cultural heritage collections have been much debated in recent years. The interest in the issue has been driven by the growing movement towards green museums, that is, managing indoor museum environments in a responsible and efficient manner, particularly in terms of reducing energy consumption and carbon emissions while maintaining high standards of collection care. This paper provides a brief progression through two fundamental approaches to establish the allowable ranges of climatic variations: an analysis of the mechanical response of painted wood, the category of heritage objects most vulnerable to relative humidity and temperature fluctuations, and an analysis of the historic climate to which the objects have acclimatised. The climate specifications and standards based on both these approaches are reviewed.

Introduction

Environmental standards for cultural heritage collections on display, in storage or in transit have been much debated in recent years. The transcriptions of two roundtable meetings of the International Institute for Conservation: 'Climate Change and Museum Collections' in 2008 and 'The Plus/Minus Dilemma: The Way Forward in Environmental Guidelines' in 2010 illustrate the problems discussed [1, 2]. The interest in the issue has been driven by the growing movement towards green museums, that is, managing indoor museum environments in a responsible and efficient manner, particularly in terms of reducing energy consumption and carbon emissions but at the same time maintaining high standards of collection care.

Heritage science and conservation practice have developed two fundamental approaches to establish the allowable ranges of climatic variations: an analysis of the mechanical response of heritage objects most vulnerable to relative humidity (RH) and temperature fluctuations, and an analysis of the historic climate to which the objects have acclimatised.

Since painted wood is generally regarded as requiring particularly tight climate control, much research has focused on understanding the response of this category of objects to changes in ambient environmental conditions and the results have strongly influenced guidelines on allowable microclimatic variations in museums. Two fundamental conditions of concern are analysed here: external or internal restraint that prevents wood from swelling and shrinking across its grain in response to RH fluctuations, and differences in the dimensional response of the wood substrate and the pictorial layer to these fluctuations.

In turn, the acclimatisation of sensitive objects to the environment within which they have been preserved for a long time has been also widely used to establish the criteria for climate control. Michalski [3] coined the term 'proofed fluctuation', defined as the pattern of largest RH or temperature fluctuations to which the object has been exposed in the past. It was assumed that the risk of physical damage beyond that already accumulated from fluctuations which do not go beyond the proofed pattern is extremely low. The proofed fluctuation concept eliminates any need for elaborate mechanical response calculations and offers a risk assessment based on past climate records alone. The concept was explicitly expressed in many standards and recommendations on the control of indoor environmental conditions.

Climate specifications based on the analysis of structural response of painted wood

Painted wooden objects are complex multi-layer structures composed of humidity-sensitive materials, wood, animal glue, gesso and paints, which respond dimensionally to variations in RH and temperature in their environment. All materials constituting the painted wood are humidity-sensitive: they shrink when they lose moisture and swell when they gain moisture. However, a notable effect is that each material responds differently to the loss and gain of moisture. The mismatch in the response of gesso and unrestrained wood substrate, particularly in the most responsive tangential direction of the wood, has been identified as the worst case condition for fracturing of the pictorial layer: upon desiccation, the shrinkage of wood overrides that of the less responsive gesso which experiences compression, whereas upon wood swelling, the gesso layer experiences tension. If the elongation of a wood support goes beyond the critical level the gesso can crack.

Stresses induced by changes in RH are not limited to the pictorial layer only. The wood substrate may also experience stress due to restraint on its dimensional response, perhaps as a result of the restriction of movement by excessively rigid construction methods, or if wooden elements have been assembled with different mutual orientation of their fibre directions. Wood can also experience internal restraint as the moisture diffusion is not instantaneous and uneven moisture change induces uneven dimensional response, when the outer parts of the wood respond more quickly than the interior to variations in ambient RH. Uneven dimensional response in opposite faces of decorated panels, due to a lower permeability of the painted face to the moisture flow, is another cause of restraint. The constraint of wood from free movement can cause deformation and cracking of the wood, and subsequent cracking and flaking of the pictorial layer.

The concept that a stable climate offers long-term stability for painted wood has, for a long time, been derived from practical observations. However, only relatively recently were two key issues systematically examined: the dimensional response of the objects to changes in temperature and RH, and the critical levels of strain at which materials begin to deform plastically or fail physically. Mecklenburg et al. [4] proposed the yield strain as a 'failure criterion' for the wood substrate or pictorial layer, that is, allowable RH variations should not cause strains exceeding the yield strain so that the response of the materials should at

all times stay in the elastic (reversible) region. Analysis of the damaging impact of RH variations on painted wood was further refined by taking into account the vulnerability of the pictorial layer to fatigue fracture, a consequence of the cumulative strain effects [5]. Cyclically repeated RH fluctuations in museums and historic interiors may range from slow seasonal changes caused by an RH decrease in winter due to heating and a return to a higher RH level in summer, to brief RH fluctuations, even under an hour in duration, arising from the opening and closing of doors and windows, the flow of visitors, or the operation of intermittent heating.

The structural analysis of painted wood has allowed maps of allowable RH variations to be produced, which take into account the amplitude, duration and initial RH level [4-6] as well as proposing environmental specifications for collections of historic objects [7,8].

The most general conclusion from a review of existing data is that moderate variations within the approximate RH range 50 plus or minus 15 % are safe. This safe range was derived from the extremes of conservative criteria of the materials' yield and fatigue fracture, and assumptions of worst-case wooden substrate response. As such, the range provides a cautious 'baseline' for the environmental standards for safe display of painted wood. This baseline can be re-defined when the understanding of critical strain levels is refined with advances in experimental research on physical fracture in painted wood. A thorough overview of the issue is provided by the author in the recent review [9].

The acclimatisation concept: target temperature and RH ranges based on past climatic conditions

The acclimatisation of painted wood to the particular indoor environment within which it has been preserved is a well-established concept in the conservation field. It was assumed that the risk of further physical damage (beyond that already accumulated in the past) from fluctuations smaller than the historic pattern of severe fluctuations is extremely low. If the past fluctuation was enough to cause fracture, the object has fractured, and the crack opens and closes reducing the stress which would be otherwise engendered in the undamaged material. Traditionally, the acclimatisation concept was the basis for recommendations that past climate conditions should be retained as accurately as possible when vulnerable objects are moved from their usual location for restoration or exhibition. With the growing use of electronic monitoring systems, long-term surveys to understand RH and temperature levels and their fluctuations have become easier and can be undertaken on a wider scale. The accumulated data can be processed mathematically to establish more quantitative target microclimates suitable for the preservation of vulnerable objects by specifying average levels of climatic parameters, their seasonal drift as well as bands of tolerable short-term fluctuations superimposed on these average levels [10]. The acclimatisation concept was also explicitly expressed in several recommendations and standards on choice and control of indoor environmental conditions favouring conservation of sensitive historic materials, discussed in detail below.

It should be stressed at this point that the harmlessness of the pre-existing climatic conditions has been a key assumption

in the approach. The assumption has to be checked carefully in each case, as physical damage can be cumulative rather than catastrophic, therefore fluctuations, even if not exceeding the historic levels, can involve risk of damage. Conservation treatments can erase the safety margins developed in objects by their acclimatisation to historic conditions. If cracks in polychrome sculpture, furniture or panel paintings act as expansion joints to relieve stress in objects, a consolidation treatment may make them more vulnerable to climate fluctuations. Treatments can also change, sometimes radically, the dimensional and mechanical properties of the original artistic materials.

It is essential to assess the extent to which acclimatisation to historic conditions has induced such safety mechanisms, particularly in those objects considered most valuable or vulnerable in a collection. These assessments can be supported increasingly by scientific methods for the direct tracing of climate-induced damage: non-invasive, simple, economical and capable of operating in real-world conditions in museums or historic buildings. The idea is to record an observable characteristic in an object which is related to damage (i.e., a damage indicator) in a continuous way or at a specified time interval, rather than to monitor the environment affecting the object. The acoustic emission method, which is based on monitoring the energy released as sound waves during fracture processes in materials, has been particularly successful in direct tracing the fracturing intensity in wooden heritage objects exposed to variations in temperature and RH [11].

Specifications and standards

Specifications and standards generally contain recommendations on three principal components by which the indoor climate is statistically represented: long-term average levels usually over one year, seasonal cycles and short-term fluctuations. Table 1 shows a selection of standards and specifications for temperature and RH since the 1970s, all aimed at ensuring the safe preservation of materials and objects sensitive to moisture-induced damage. The earlier history and development of recommendations for the climate in museums is described by Erhardt et al. [12].

The most general tendency is the gradual development of such recommendations from single-value targets and conservative tolerances to more rational, science-based approaches allowing seasonal changes and broader short-term fluctuations. The specifications have gradually recognised that the recommended temperature does not need to be at the universal value of around 20 °C dictated by human comfort. The widest range was specified by the National Trust in the UK, in which the lower limit of the allowable range was set at 5 °C to prevent the risk of frozen pipes.

The specifications reflect a general belief that RH should be as near constant as possible and that the middle RH region (close to 50 %) is optimal, being close to the annual outdoor average in those parts of the world where the guidelines were written. However, there is also an awareness that objects stored for significant periods of time in environments where the average annual RH deviates from the central value of 50 % might have become acclimatised to these conditions. Therefore, any change from a particular historic climatic environment may be

Table 1. Selection of international standards and specifications since the 1970s for temperature and relative humidity

Year	Source or institution issuing the specification	Temperature [°C]	RH [%] Long-term average	RH [%] Seasonal cycle	RH [%] Short-term fluctuations	Remarks	Reference
1978	Garry Thomson The Museum Environment	19 (winter) Up to 24 (summer)	50 or 55	-	± 5	Class 1 - appropriate for major national museums, old or new, and also for all important new museum buildings	[13]
		Reasonably constant to stabilise RH	40 to 70			Class 2 – aimed at avoiding major dangers whilst keeping costs and alteration to a minimum, for example, climate control in historic houses and churches may have to be limited to class 2 specifications	
1979	Canadian Conservation Institute	21 (Seasonal variation from 20 to 25 allowed)	Between 47 and 53	38 to 55	± 2	The allowed seasonal changeover of the set points is 1 °C and 5 % RH per month, respectively Occasional variations of ± 5 % RH are tolerable if these are the exception	[14]
1994	National Trust	5 to 22	58	50 to 65 (alarm level 1) 40 to 75 (alarm level 2)		The recommended strategy involved control of RH to as constant a level as possible principally by adjusting heat input	[15]
1999	American Society of Heating, Refrigerating, and Air-Conditioning Engineers Inc. (ASHRAE)	15 to 25	50 or historic yearly average	No	± 5	Class of control AA – No risk of mechanical damage to most artefacts and paintings	[8]
				No	± 10	Class of control A – Small risk of mechanical damage to high-vulnerability artefacts; no mechanical risk to most artefacts, paintings	
				+ 10 in summer - 10 in winter	± 5		
				+ 10 in summer - 10 in winter	± 10	Class of control B – Moderate risk of mechanical damage to high-vulnerability artefacts; tiny risk to most paintings	
				25 to 75		Class of control C - High risk of mechanical damage to high-vulnerability artefacts; moderate risk to most paintings	
				Below 75		Class of control D - High risk of sudden or cumulative mechanical damage to most artefacts and paintings because of low-humidity fracture	
2006	National Trust	5 to 22	50 to 65	-	-	The earlier fixed set point of 58 % RH was replaced with a target range. The RH set point should be adjustable in each room and depend on the conditions to which the collection has acclimatised	
2007	Smithsonian Institution	21	45	-	± 8		

Year	Source or institution issuing the specification	Temperature [°C]	RH [%] Long-term average	RH [%] Seasonal cycle	RH [%] Short-term fluctuations	Remarks	Reference
2009	National Museum Directors' Conference UK	16 to 25	40 to 60			Specifications for the majority of objects containing hygroscopic material. However, panel paintings are listed among more sensitive materials which require specific and tight RH control	[8]
2010	European standard EN 15757:2010	No specification	Historic yearly average	Historic seasonal cycle*	± 10 or target range calculated from the historic climate** (whichever greater)	* This cycle is obtained by calculating, for each RH reading, the central moving average (MA), which is the mean of RH readings taken 15 days before and after the time at which the average is computed ** The lower and upper limits of the target range of RH fluctuations are determined as the 7th and 93rd percentiles of the fluctuations recorded in the monitoring period respectively A fluctuation is calculated relative to MA, i.e., the seasonal cycle rather than the yearly average value	[16]

problematic, even though the new conditions may appear optimal for long-term preservation.

The same approach is taken to the RH variations of various time scales, from a yearly cycle to short-term fluctuations. Authors of the early recommendations on the narrow ranges of RH variations stated openly that they were based on what could be expected of air-conditioning systems rather than on any knowledge of what objects could tolerate without damage [13]. With the growing understanding of the effects of climate conditions on materials and objects, broader ranges of RH variation have been increasingly accepted. It has been recommended that allowable ranges could be based on less-than-ideal historic conditions provided the collection has survived well. The assumption behind these specifications is that conservation professionals can assess the risks posed by historic conditions by undertaking condition surveys of the most vulnerable or valuable objects within the collection.

The ASHRAE specifications went one step further by specifying five classes of climate quality and detailing which climate related risks are avoided in each class and which are present [8]. These specifications also state that the long-term RH level can be either 50 % (for international consistency) or it can be the local historic average RH (for the museum's permanent collection).

Conclusions

The most general conclusion from the scientific research and preventive conservation practice discussed in this paper is that increasing criticism of the fundamentalist concept of strictly controlled museum climates has, since the 1980s, led to more relaxed specifications permitting individual long-term targets for specific collections, seasonal changes and broader ranges of short-term fluctuations.

Each sensitive object with its unique original structure and conservation history, acclimatised to its particular environment, requires specific levels and ranges of temperature and RH. However, the body of scientific evidence indicates that moderate variations within the approximate range 50 plus or minus 15 % are safe. This variation corresponds to class B of the ASHRAE controls, which is often the only possible moderate-cost strategy available to historic buildings (also used by museums) offering some limited potential for tighter climate control.

Further broadening of the allowable variations might result from observations that many objects have survived remarkably well in conditions which were far from 'ideal'. Therefore, climate specifications based on the acclimatisation concept remain useful tools, particularly when electronic monitoring systems can provide long-term historic climate data in remarkable detail. The two approaches can also be amalgamated so that maintaining the past microclimate (in terms of levels, seasonal cycles and fluctuations of temperature and RH) is combined with the 'absolute' allowable variations based on the mechanical behaviour of paintings. As a result, very stable past microclimates will not dictate unnecessarily strict future targets for climate control.

Acknowledgements

References

[1] 'Climate change and museum collections, a discussion held on September 17, 2008, London, edited transcription, International Institute of Conservation', http://www.iiconservation.org/dialogues/ IIC_climate_change_transcript.pdf (accessed 15 August 2012).

[2] 'The plus/minus dilemma: the way forward in environmental guidelines, a discussion held on May 13, 2010, Milwaukee Wisconsin, USA, edited transcription, International Institute of Conservation', http://www.iiconservation.org/dialogues/Plus_ Minus_trans.pdf (accessed 15 August 2012).

[3] Michalski, S., 'The ideal climate, risk management, the ASHRAE chapter, proofed fluctuations, and towards a full risk analysis model', in Proceedings of Experts' Roundtable on Sustainable Climate Management Strategies, Tenerife, 2007, ed. F. Boersma, Getty Conservation Institute, Los Angeles (2009). http://www.getty.edu/conservation/our_projects/science/climate/ paper_michalski.pdf (accessed 19 April 2013).

[4] Mecklenburg, M.F., Tumosa, C.S., and Erhardt, D., 'Structural response of painted wood surfaces to changes in ambient relative humidity', in Painted Wood: History and Conservation, ed. V. Dorge and F.C. Howlett, The Getty Conservation Institute, Los Angeles (1998) 464–483.

[5] Rachwał, B., Bratasz, Ł., Krzemień, L., Łukomski, M., and Kozłowski, R., 'Fatigue damage of the gesso layer in panel paintings subjected to changing climate conditions', Strain 48.6 (2012) 474–481.

[6] Jakieła, S., Bratasz, Ł., and Kozłowski, R., 'Numerical modelling of moisture movement and related stress field in lime wood subjected to changing climate conditions', Wood Science and Technology 42 (2008) 21–37.

[7] Erhardt, D., and Mecklenburg, M., 'Relative humidity re-examined', in Preventive Conservation Practice, Theory and Research, ed. A. Roy and P. Smith, International Institute of Conservation, London (1994) 32–38.

[8] American Society of Heating, Refrigeration and Air-Conditioning Engineers, 'Museums, galleries, archives and libraries', in ASHRAE Handbook – HVAC Applications, ed. M.S. Owen, ASHRAE Inc, Atlanta (2007) 21.1–21.23.

[9] Bratasz, Ł., 'Allowable microclimatic variations for painted wood', Studies in Conservation (forthcoming).

[10] Bratasz, Ł., Kozłowski, R., and Camuffo, D., 'Target microclimate for preservation derived from past indoor conditions', in Contributions to the Museum Microclimates Conference, ed. T. Padfield and K. Borchersen, The National Museum of Denmark, Copenhagen (2007) 129–134.

[11] Łukomski, M., Czop, J., Bratasz, Ł., and Strojecki, M., 'Acoustic Emission monitoring: on the path to rational strategies for collection care', see this volume pages 069–079.

[12] Erhardt, D., Tumosa, C.S., and Mecklenburg, M.F., 'Applying science to the question of museum climate', in Contributions to the Museum Microclimates Conference, ed. T. Padfield and K. Borchersen, The National Museum of Denmark, Copenhagen (2007) 11–18.

[13] Thomson, G., The Museum Environment, 2nd edn, Butterworth-Heinemann, London (1986) 268–269.

[14] Lafontaine, R.H., 'Environmental norms for Canadian museums, art galleries and archives', Technical Bulletin No.5, Canadian Conservation Institute, Ottawa (1979).

[15] Staniforth, S., Hayes, B., and Bullock, L., 'Appropriate technologies for relative humidity control for museum collections housed in historic buildings', in Preventive Conservation Practice, Theory and Research, ed. A. Roy and P. Smith, International Institute of Conservation, London (1994) 123–128.

[16] Staniforth, S., 'Relative humidity as an agent of deterioration', in The National Trust Manual of Housekeeping, ed. K. Lithgow, H.

Lloyd, J. Parry, S. Staniforth and N. Seeley, The National Trust, Amsterdam (2006) 113.

[17] NMDC Guiding Principles for Reducing Museums' Carbon Footprint, National Museum Directors' Conference (NMDC) UK (2009), http://www.nationalmuseums.org.uk/media/documents/what_we_do_documents/guiding_principles_reducing_carbon_footprint.pdf (accessed 15 August 2012).

[18] EN 15757:2010, Conservation of Cultural Property - Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials, European Committee for Standardisation, Brussels (2010).

Author

Łukasz Bratasz is head of the research laboratory in the National Museum in Krakow and research fellow at the Jerzy Haber Institute of Catalysis and Surface Chemistry Polish Academy of Sciences. His research focuses on the response of materials to changes in environmental parameters, development of non-invasive measures of damage tracing as well as implementing measures to prevent damage to the collections .
Email: ncbratas@cyf-kr.edu.pl

Licence

Towards a common understanding of standards?

Jane Henderson and Shumeng Dai

Abstract

If universal principles of conservation are to be discussed effectively a common understanding of standards should be established. This paper offers a vocabulary of standards and introduces a method to describe them. The paper reviews the development of standards identifying the relationship between the origin of a standard and its resultant approach. It uses pairs of keywords to describe distinctive features of standards and uses five word pairs to examine and compare national standards in the UK and China. The process of understanding standards and describing them precisely enhances efficiency through improved communication.

Introduction

The concept of standards is like 'good company', or 'a beautiful view': easy to recognise but hard to define. This paper investigates our understanding of standards, both in their terminology and the meaning that they confer. Clear definitions of standards exist but whether the term confers the same meaning to different people is questionable. The paper considers the origins and implementation of standards and offers an extended vocabulary and a model of description that could contribute to a more aligned description and understanding of standards. It also offers an opportunity to broaden our appreciation of the role of standards and thus increase their impact.

Standards are important in that they promote efficiency, quality and innovation [1], they are the products of compromise: we abandon uniqueness to conform. Standards can be compulsory or voluntary and their origin influences their implementation. Cassar and Keene [2] describe standards based on their geographic influence. A museum could use international or national standards or their work could be governed by an internal specification operating as a standard. In order to make comparisons this paper focuses on national standards for collections care.

Case studies

In the UK a concern for the creation of standards in collection care has existed since the 1970s [3] resulting in comparatively more standards than in China which is beginning a process of defining and developing standards. Reviews of Chinese museum collections under threat due to poor collection management in the early 2000s [4] and the publication of Thomson's The Museum Environment in Chinese [5] have been an impetus to standards creation. The resulting schemes in China are in a trial stage.

What is a standard?

A standard is a document to consistently measure ways of producing objects, processes and services. Standards help

to ensure uniformity and reduce complexity [1], they give us confidence to follow a common method and make it easier to make decisions [6]. Standards are built on the consensus of current best practice that incorporate the experience, opinions and expertise of all interested parties [7]. In common parlance the term 'standard' can be used in a variety of ways and can be defined in relation to a wider jurisdiction, their content or how they were formed.

Talking about standards in conservation

The scope of preventive conservation is broad and there are many practices that can be described as 'standard'. Within the narrowest meaning, only published formal standards with a serial number should be referred to as such. A more general meaning can include all the public or non-public, formal or informal documents that regulate the care of objects and established traditions, conventions or customs whether or not they are in a written form. For example, in any culture behaviour in relation to occasions such as birthdays or weddings can be described as 'standard practice' without the existence of any formal definition: this can be described as a standard-based approach [8]. Standardised practice also exists in more formal and documented contexts including manuals, specifications, procedures, etc. Broadly speaking, law and policy can also be categorised as a standard. An insistence on a tight definition of standards may generate a pleasing sense of precision but may reduce effective communication and understanding. Recognising standard-based approaches widens the scope to be considered when seeking to change, improve or consolidate practice within collections care.

Standards in context

Standards are detailed and more flexible than laws and policies, their relationship is like a pyramid (Figure 1). Laws can underpin the implementation of standards by providing a regulatory framework. Laws represent the state's interest and citizens must comply. Policies are made by governments, organisations, companies, etc., to manage the institution's internal activities. Policies guide people to operate within the constraint of the law. Standards are detailed to provide technical specifications to support policies and laws. Normally standards are voluntary, but when identified in law, they become compulsory.
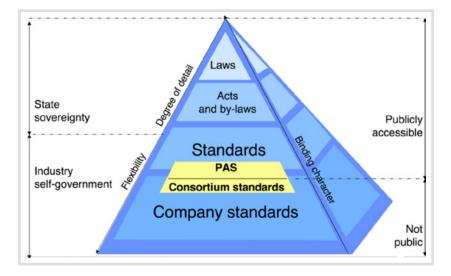
Figure 1. Standards within the legal system: the hierarchy of regulations [9]

Content of standards

Based on their contents, standards can be categorised into four basic types: measurement standards; process standards; performance standards; interoperability standards [10]. Each of these types can be found in collections care.

Measurement standards

Measurement or metric standards are used to measure ordinal values such as the size of clothing or volume measurements. These standards are useful for manufacturers producing products and for customers purchasing them [10]. The words and numbers used in these standards are unambiguous and precise. Many collections care standards describe performance using measurable standards such as 50 to 60 % RH.

Process standards

These prescriptive standards aim to provide normative activities or processes. They supply the 'methodology to perform tests and perform processes in a consistent and repeatable way' [10]. These standards describe the sequence of an operation. An 'Oddy test' is a standardised process to evaluate the suitability of materials for inclusion in display cases [11].

Performance standards

Performance-based standards are fundamental to benchmarking [6]. They may set several levels of behaviour to encourage individuals to aim for the highest. For example, in Japan following the Hyogoken-nanbu earthquake of 1995, the Building Standard Law was revised to prescribe performance requirements based on earthquake response [12]. Thomson offered both Class I and Class II environmental standards to be applied dependant on the nature of the collections, building and institution type [5].

Interoperability

Interoperable or compatibility standards are set for two or more different activities to ensure they use the same method or specification. The process and performance are not prescribed but a fixed format is required [10]. For example, the designs of keyhole and key are interoperable. When considering digital preservation, both the digital artefact and an interoperable system of software and hardware must be preserved to ensure that the digital artefact can be accessed.

Combinations of content

Some standards can represent more than one typology. For example, the UK standard single bed size is 36 × 75 inches. Utilising clear measurements it is also performance based, because its size is suitable for a person and it is interoperable because the mattress fits the bed. For a registrar operating an international art loan these different standards approaches could arise. The loan conditions may specify measurable environmental targets set at several degrees of tightness. Testing of display case materials according to the Oddy test protocols may be included in the facilities agreement as may a plan to ensure that any

environmental logging systems travelling with the loan items could be read and interpreted by each venue.

Origin of standards

If we categorize standards according to the process by which they are created, the basic types are de facto and de jure standards [13].

A de facto standard, evolved by a market process, is widely accepted and used, having achieved a dominant consensus position without approval from any official body, while a de jure standard is established by an official standards organisation and is promulgated by a government agency [14]. These categories represent two groups of stakeholders involved in the evolution of standards [15].

De facto standards emerge from consensus and competition; the winning standards will represent the emerging dominant technology [15]. A winner-takes-all approach to the emergence of de facto standards will result in the elimination of competitor systems such as the battle between VHS and Betamax. A de facto standard can be sponsored by an organisation or can be unsponsored such as the QWERTY keyboard.

De jure standards do not necessarily represent consensus in the market. The 'winners' are those selected by authorising bodies. Although de jure standards avoid competition costs they rely on judgement for selection and there may be a gap between the priorities of decision makers and practitioners [15].

Both de jure and de facto standards can be based upon evidence generated by research to support their specification. The process of creating a de jure standard may begin with specially-commissioned research and a de facto standard can evolve from the wide-spread acceptance of the conclusions of research. Conversely, a determined politician could impose a de jure standard regardless of the evidence; poor practice, with no evidence base, can evolve into a de jure standard in the way that superstitions grow. The practice of collections care is best served by those standards that are based on relevant research and evidence whether this is research commissioned specifically for the purpose of standard creation or evidence created by research simply inspiring a standardised response.

By considering these aspects of standards (jurisdiction, content and formation) it is apparent that although simple definitions can be offered, standards vary greatly with consequent variation in their

Table 1. Summary of categories of standards

Application or Jurisdiction	Type of Contents	Formative process
Corporate in-house or organisational standards	Measurement standards	De facto standards
Society or Industrial standards	Process standards	De jure standards
National standards	Performance standards	
Regional standards	Interoperability standards	
International standards		

impact (Table 1). Where a response to a collections care problem is the development of a standard, an awareness of this variety and a developed vocabulary will assist in an effective process of standard definition and implementation.

Standards and semantics

Once the variability of standards or standards-based approaches is accepted, the challenge that arises is how to represent and understand this. Ashley-Smith [6] offered seven pairs of polarised words to illustrate the diversity of standards. This concept has been adopted and extended here to develop a methodology to portray variability and to enable discussion about how this may impact on the uptake and operation of a standard. From the initial seven pairs, the authors created 23 pairs of words to highlight dichotomies within standards (Table 2). These pairs are grouped into categories which reflect: the elasticity of standard design; measurement methods; reasons for standardisation; compliance regimes; formative process and application.

Pairing serves to highlight the breadth of concept embodied within the simple term 'standard'. Any word pair can be used to evaluate a standard along an imaginary scale between them. For

Table 2. Semantics applied to standards

1	Broad scope	Narrow scope	Degree of tightness
2	Universal	Local	
3	Generic	Specific detailed	
4	Flexible	Rigid	
5	Risk	Certainty	
6	General directions	Fixed numbers	
7	Evangelism	Pragmatism	
8	Process	Technical	The measurement methods
9	Outcome	Output	
10	Minimum requirement	Good/Best Practice	
11	Compatible	Self-dependent	The motivation for standardisation
12	Uniform	Diversiform	
13	Impartial	Unfair	
14	Objective	Subjective	
15	Evidence based	Lacks evidence	
16	Guidance	Coercion	Binding characters
17	Enable	Punish	
18	Self-assessment	External force	
19	De facto	De jure	Formative process and application
20	Evolved	Imposed	
21	Market	Government	
22	Public	Non-public	
23	Long period	Temporary/ Provisional	

Figure 2. Representation of standard variability using spider graphs

the purpose of this paper, to examine UK and Chinese standards, five critical word pairs were identified. By eliminating concepts that were pre-determined or beyond the scope of the study and word pairs which represent an inherently correct position the list was narrowed. Word pairs that were most descriptive and applicable to a museum context were chosen. Although a comparison of the degree of pragmatism or risk approach would be insightful, the authors concluded that in comparing the UK with China the pairing of flexibility – rigidity offered the most culturally neutral evaluation.

Spider graphs

Each of the five word pairs chosen can be plotted on a spider diagram (Figure 2) using judgement to place each standard at a point between the pairs.

1. Broad scope   Narrow scope
2. Generic   Specific detailed
3. Flexible   Rigid
4. Self-assessment   External force
5. Long period   Temporary/Provisional

For some of the pairs it may be presumed that a midpoint creates an optimal standard. For example, it can be a disadvantage for a standard to be too flexible or too rigid. For others, such as longevity, an appropriate time scale may relate to the stability of the context in which they apply. The pairings are offered as a tool kit to dissect standards, to represent and highlight how different approaches may work in a given context. It is not intended that the pairings selected for this study would be the best in another but this methodology of representing the variety could be used elsewhere.

Analysis of museum standards

Eight UK-based collections care documents from the last 35 years were selected for study. These texts include benchmarks and guidelines that go beyond the technical description of standards. Two Chinese standards for collections care in museums were considered. As these standards are undergoing a trial implementation their scaling is based on an understanding of their operation in four Chinese Museums (Wuhan Museum, Xi'an Ban Po Museum, Shanghai Museum and Capital Museum). This range of documents was selected to examine their variability considering their different nomenclature and origin.

BS 5454:2000 Recommendations for the storage and exhibition of archival documents and PD 5454 Guide for the storage and exhibition of archival materials (UK). BS 5454 was a de jure standard in its simplest sense. It had a narrow scope defined in its title. With a clear focus, the requirements were specific and detailed. With rigid, unambiguous provisions and fixed numbers it has elements of a measurement standard and is consequently easy to understand. BS 5454 was used for official inspections so an institution could lose recognition if it failed to comply. In 2012, PD 5454 superseded BS 5454, offering guidance on the preservation of archives, although it offers a wider scope. Compared with the BS, PD 5454 is more flexible in a range of contexts making it easier to apply whether the collections are mixed or vulnerable, in all seasons, in historic buildings or in a purpose-built repository. PD

5454 provides fixed numbers but these are set in a range with explanations; it offers solutions and has detailed guidance. The document is more persuasive than its precursor. PD 5454 is not a 'British Standard', but its potential is huge as it replaces BS 5454. Recently launched, it may not be updated soon.

PAS 197:2009 Code of practice for cultural collections management (UK). PAS 197 is described as a specification with a narrow scope concentrating on collections management, it is concise and systematic. The standard has some flexibility and is not based on coercion. PAS stands for Publicly Available Specification, which means it could later become a 'British Standard'. PAS 197 was scheduled for review two years after its completion.

SPECTRUM museum documentation standard (UK). Described as the UK museum documentation standard, SPECTRUM contains 21 procedures and many more 'sub-procedures'. This process standard covers object documentation and activities such as condition assessment, prescribing the priority of actions. SPECTRUM is specific and certain and has spurred museums to undertake large information management projects. The standard contains minimum requirements. Established by a public body, its procedures are incorporated in the UK Museum Accreditation Standard [16]. Since its inception in 1994 it has been widely accepted in the museum industry in the UK and internationally operating both as a de jure and a de facto standard.

Benchmarks in collections care for museums, archives and libraries (UK). Identified specifically as a benchmarking, not a standards', document this publication describes three levels of performance for collections care against which institutions can self-assess. Collections care is a broad concept involving a wide range of activities influencing the preservation of objects. Benchmarks contains many recommendations but does not force the institution to complete them; the provisions are pragmatic with detailed scope offering a self-assessment approach supporting staff to improve performance. Based on several precursor documents, Benchmarks was published in 2002 and revised in 2011. Benchmarks represents a de jure approach that has evolved and become more detailed over 15 years.

MGC standards in the museum care series (UK). These wide-ranging standards first published in 1992 comprise eight booklets covering a series of specific collections types published by a governmental advisory body, the Museums and Galleries Commission (MGC, now MLA) [17]. They contain detailed requirements describing best practice in process and performance but there is no enforcement regime. The standards are rigid and specific, guiding non-experts to implement them. The requirements are relatively high, containing some specific measurement-type targets requiring significant resources to achieve them. Despite the dissolution of their sponsoring body, these standards still have relevance in the UK museum sector; they have transitioned from a de jure to a de facto standard. Without external force, these strict standards are unlikely to be applied consistently.

Thomson's The Museum Environment (UK). This universally acknowledged de facto standard for collections care describes environmental parameters for museums. Many countries applied

the standards contained within the book with varying success. Although there is no external force to impose implementation this book became a touchstone of good practice resulting in the enforcement of its Class A standards through de jure routes such as BS 5454 or de facto methods such as international loan agreements. Creating a long term consensus in the market, the book's specific and detailed contents eliminate doubts and encourage acceptance of its recommendations. It is a good example of how standard practice can emerge from a source which does not comply with the traditional definition of standards.

Regulation on Museum Collection Conservation Environment in Trial Implementation (China). This regulation is a de jure standard produced by the standard-making committee of State Administration of Cultural Heritage (SACH) in China. This is a technical standard used to regulate museum environment conditions for collections storage, display areas and conservation labs. The provisions are measurable, specific and rigid, for example, specifying store size without reference to collection type [18]. Some clauses offer more general guidance. This is a minimum standard document. In its evolutionary stage imposing the standard may be dangerous. However, in practice, museums undertake the project with support from the experts from SACH who conduct inspections and offer further guidance whilst encouraging museums to complete the implementation.

Museum Evaluation Standard (China). The Museum Evaluation Standard is also a de jure standard of SACH. It has three performance grades. Museums are awarded Grade 1 by achieving a total score of over 800 points which does not require the museums to meet the entirety of the highest grade [19]. The Evaluation Standard is assessed by committee. It focuses on processes such as the management of infrastructure and facilities, collections management and research, exhibitions and services. It also contains elements of a measurement standard, for example, offering scores against specific numbers of (undefined) 'precious collections' [19]. This is an interesting case of a non-specific measurement standard. It is planned that the standard will last a long time and will be revised and updated every three years. For museums applying to the scheme, there will be the external pressure of supervision and assessment by the government. Museums may lose their accreditation status if they cannot maintain the scheme. The standard is pragmatic but lacks precision.

Discussion

Of the ten documents considered four are formally defined as standards although only BS 5454 has specific recognition as such. Others defined practice later adopted by standards and others have the potential to one day evolve into a formal standard. All offer advice, guidance and definitions against which collections care practice can be measured and improved. It is possible to split these documents into two categories depending on whether or not they are formal standards but this distinction may be one of the least interesting to make.

Considering the graphs, for several of the pairs a median point on the scale is a baseline and deviating from this raises questions about a standard's efficacy. The more extreme the scaling the more challenges there may be in implementing it. Plots for PAS

197:2009, PD 5454 and Chinese Museum Evaluation Standard are closest to the median points suggesting they offer balanced achievable approaches. Standards which demonstrate greater rigidity or specificity will be harder to implement. If they are supported by a strong enforcement process they may be enacted, perhaps with resentment, but without external force their implementation may be perfunctory. Broader scope will tend to increase the areas to which the standard applies and therefore increase the resources required to implement it.

The Museum Environment is a special case. It played a unique role in the early days of environmental standards when it defined the pinnacle of knowledge and was adopted in the absence of any alternative. In today's more crowded market a specific and rigid standard with no enforcement might expect to have less impact.

It is useful to consider the range of museum institutions attempting to adopt these standards: specifically comparing those with reasonable environmental conditions and staff expertise with those with fewer resources. Standards which lack any extreme score may generally experience a good rate of take-up due to their more voluntary and generic nature offering some detail and flexibility. However, for institutions with fewer resources these more generic standards may require professional support to be effective. These smaller less well-resourced museums may welcome the lack of detail and enforcement but this may allow weaker aspects of practice to continue unnoticed. Those museums provided with professional support may be able to use median point standards to create good outcomes. Larger museums with a stronger starting point of conditions and expertise also have the awareness to improve themselves. For these museums, standards which offer clear statements in an achievable framework are challenging and can lead to improvements without external force.

Chinese collections care standards

The two Chinese standards whilst pragmatic do not offer a full spectrum of detail so aspects of collections care such as documentation are not discussed. Standards for different types of collection or museum are not yet in place in China. Adoption of de facto standards from abroad with an established consensus and reputation could help avoid adverse unintended consequences related to the adoption of new specific standards.

SACH aim to regulate all museums in China [20] but this will take time and their priority appears to be raising minimum standards, perhaps at the expense of driving improvements in best practice. Although the Evaluation Standard defines attainment levels, these utilise vague terminology such as 'proper' and 'effective', offering less specific guidance. A reliance on written standards can mean that those museums operating at best practice levels have an underused potential to be used as benchmarks for all Chinese museums.

Conclusion

Mapping standards across word pairs is a tool to dissect their varied nature and spirit. Considering those standards that have endured but been revised, it can be seen that the pressures of sustainability, pragmatism and professional review have led

towards the median points on many of the scales shown. As Chinese museums implement a more consistent approach to collections care they may find that the balance between detailed rigid approaches and generic ones becomes easier to achieve. We have seen how elements of The Museum Environment have operated as a standard and how documents offering levels of practice, whether described as benchmarks or standards, can increase a sense of attainability.

The concept of standards can be as simple or as complex as anyone wishes to consider. In this paper we have analysed the concept in its broadest sense in the belief that the common understanding of 'standards' goes far beyond a narrow technical description. When defining and improving practice in collections care, operating with this broader conception offers the benefit of greater impact and clearer communication.

Acknowledgements

References

[1] Feng, P., 'Studying standardization: a review of the literature', in Standardization and Innovation in Information Technology, the 3rd IEEE conference on 22–24 Oct 2003, ed. T.M. Egyedi, K. Krechmer and K. Jakobs, IEEE, Delft (2003) 99–112.

[2] Cassar, M., and Keene, S., 'Using standards', in Managing Conservation: Conference Preprints, ed. S. Keene, UKIC, London (1990) 11–15.

[3] Henderson, J., 'Preventive conservation in the UK: the past and the future', Technè: La Conservation Preventive, Une démarche évolutive, 1990–2010, 34 (2011) 76–85.

[4] Shan, J.X., From Care of Culture Relics to Care of Culture Heritage (in Chinese), University Press, Tianjin (2008).

[5] Thomson, G., The Museum Environment (in Chinese), Science Press, Beijing (2007). Prefaced by Ma Qinglin.

[6] Ashley-Smith, J., 'Current thinking on environmental standards', in Conservation Matters in Wales, Challenging Buildings: the search for solutions, ed. J. Henderson, Federation of Museums and Art Galleries of Wales and National Museum Wales, Cardiff (2006) 10–14, http://welshmuseumsfederation.org/index.php?page=conservation-matters-in-wales&hl=en_US (accessed 1 August 2012).

[7] British Standards Institution (BSI), 'What are the differences between consensus and commissioned standards?', http://www.bsigroup.com/en/Standards-and-Publications/About-standards/Differences-between-Consensus-and-Commissioned-standards/ (accessed 2 August 2012).

[8] Resource, Collections Management: Preserving the past for the future, Resource, London (2002).

[9] Blind, K., 'Innovation and standards', http://archive.europe-innova.eu/servlet/Doc?cid=6030&lg=EN (accessed 29 July 2012).

[10] Allen, R.H., and Sriram, R.D., 'The role of standards in innovation', Technological Forecasting and Social Change 64.2 (2000) 171–181.

[11] Lee, L.R., and Thickett, D., Selection of Materials for the Storage or Display of Museum Objects, British Museum Occasional Paper 111, The British Museum, London (1996).

[12] Kuramoto, H., 'Seismic design codes for buildings in Japan', Journal of Disaster Research 1.3 (2006) 341–356.

[13] Ida, T., 'Evolutionary stability of de jure and de facto standards', http://www.econ.kyoto-u.ac.jp/~ida/3Kenkyuu/3Workingpaper/WPfile/2000-2001/standards.pdf (accessed 1 August 2012).

[14] Coallier, F., and Gerin-Lajoie, R., Open Government Architecture: the evolution of de jure standards, consortium standards and open source software, CIRANO, Québec (2006).

[15] Wang, J., and Kim, S., 'Time to get in: The contrasting stories about government interventions in information technology standards', Government Information Quarterly 24.1 (2007) 115–134.

[16] Collections Trust, SPECTRUM: the UK Museum Documentation Standard. Collections Trust, Cambridge (2009).

[17] Collections Link, 'Museums and galleries commission standards in museum care', http://www.collectionslink.org.uk/discover/site-information (accessed 2 August 2012).

[18] State Administration of Cultural Heritage (SACH), 'Regulation on museum collection conservation environment in trial implementation', http://www.airtech-china.com/_d268707669.htm (accessed 28 July 2012).

[19] State Administration of Cultural Heritage (SACH), 'Interim standards for the assessment of museums of China', http://www.sach.gov.cn/tabid/714/InfoID/7893/Default.aspx (accessed 1 August 2012).

[20] Yin, J., State Administration of Cultural Heritage, personal communication, 11 August 2009.

Authors

Jane Henderson (author for correspondence) is Senior Lecturer at Cardiff University. Jane teaches on Cardiff University's BSc in Conservation and MScs in Collections Care and in Conservation Practice. Email: hendersonlj@cardiff.ac.uk

Shumeng Dai is Conservation Assistant at the National Art Museum of China. Shumeng studied for an MSc in Collections Care in Cardiff University where her dissertation considered standards in Chinese and UK museums. Email: daishumeng@namoc.org

Conservation of cultural heritage – European standards on the environment

Jesper Stub Johnsen

Abstract

In 2004 a working group was established under the framework of the European Committee for Standardisation to develop environmental standards for museums, archives and historic buildings. Its brief was to develop specifications, measurements and methodologies to assist museum professionals to understand and manage environmental factors affecting heritage.

This paper summarises the processes of drafting the European standards and explains the rationale behind the documents; it also discusses future approaches to developing European standards.

Introduction

In 2004 a technical committee (TC 346) was established under the framework of the Comité Européen de Normalisation (CEN) or European Committee for Standardisation with the main objective 'to develop, with a need-based approach, specific normative documents in the field of conservation of cultural heritage' [1].

One of the five working groups within the technical committee was 'CEN/TC 346 WG4 Environment' (WG4). The objective of WG4 was to formulate specifications, measurements and methods to control the environment of collections, historic houses and outdoor monuments. As convenor of this working group, the author has focused on creating standards which will develop theory, procedures and methods to improve environmental conditions.

The standards were drafted by experts nominated from across Europe and present recent research and practice within each subject. The draft documents were also considered by experts from the CEN member states before publication, and the standards will be reviewed every five years.

This process ensures the standards are not simply based on consensus around established baselines but rather reflect the cutting edge of conservation research, knowledge and practice, balancing contemporary demands for the dissemination and presentation of cultural heritage with concerns for long-term sustainability. The standards are intended to be helpful, practical and usable tools to support and improve the constant work of conserving cultural heritage across Europe.

Background – previous experience with environmental standards
Danish Film Institute - the use of standards in the preservation of photograph and motion picture collections

For more than 30 years the motion picture film collection at The Danish Film Institute (DFI) was stored in poor environmental conditions [2]. A survey conducted in 2000 revealed that much of

the degraded acetate film stock was expected to reach a critical level of decay within 15 years if the storage environment was not improved [3]. A massive duplication program was necessary to save the contents of the collection. The deterioration processes included unstable cellulose nitrate-based films, acetate film presenting clear signs of vinegar syndrome and fading colour films. It was estimated that within 10 years more than 10000 film titles of the 31000 in the collection would require duplication or digitisation to a more stable format. The average cost per film was 15000 Danish Krone (DKK), a total of 500 million DKK at 2002 prices [4].

An alternative solution to this huge duplication program was devised based on the International Organisation for Standardisation's (ISO) recommendations for the preservation of imaging materials [5 to 7]. Following the cutting-edge research presented in the standard, a new film archive was established with a predicted usable lifetime of at least 500 years, and environmental conditions which reduced the rate of film decay to almost zero. The predicted cost was around 50 million DKK; this amounted to 62 DKK per film title (at 2002 prices, with annual running costs). Experience from the last 10 years of operating the storage facilities at the Danish Film Archive shows that it is possible to maintain a temperature of 5 °C and 35 % relative humidity (RH) in a 2300 m^3 room for around 30 kWh/m^3/year [8]. This energy consumption is low In comparison with other facilities operating similar environmental conditions. By establishing a film archive that meets the international environmental standards specified for motion picture films the collections have been safeguarded for a far lower cost than duplicating the degrading stock.
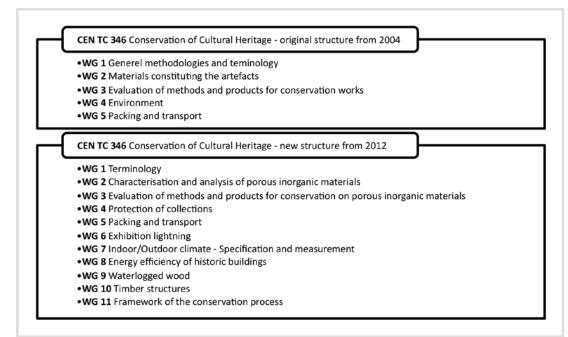
Standards and standardisation

In general, we are most familiar with those standards developed to improve product quality, for example, for memory cards in computers and cameras or electricity plugs. These are based on established norms. In most cases, standards are optional but may contribute substantially to the success of a contract or business. In some circumstances, standards are mandatory, for example, building or fire regulations. In many areas, standards are introduced with the intention of simplifying quality control for both service providers and users.

The most effective standards are based on current knowledge and best practice; they are usually developed by experts with complementary backgrounds to clearly disseminate practical information to end users. Standards should be based on the most current information, avoiding redundant research. Reference to international standards may improve perceptions of the validity of a solution and may contribute to a more considered end result than if local procedures were developed through anecdotal experience.

Developing European standards for the conservation of cultural heritage

Many physical materials, objects or buildings are considered to be part of our cultural heritage. In order to preserve these artefacts or structures some protection measures have to be established. A long-term sustainable conservation approach should include all factors that may affect the stability and preservation of

CEN TC 346 Conservation of Cultural Heritage - original structure from 2004

- **WG 1** Generel methodologies and teminology
- **WG 2** Materials constituting the artefacts
- **WG 3** Evaluation of methods and products for conservation works
- **WG 4** Environment
- **WG 5** Packing and transport

CEN TC 346 Conservation of Cultural Heritage - new structure from 2012

- **WG 1** Terminology
- **WG 2** Characterisation and analysis of porous inorganic materials
- **WG 3** Evaluation of methods and products for conservation on porous inorganic materials
- **WG 4** Protection of collections
- **WG 5** Packing and transport
- **WG 6** Exhibition lightning
- **WG 7** Indoor/Outdoor climate - Specification and measurement
- **WG 8** Energy efficiency of historic buildings
- **WG 9** Waterlogged wood
- **WG 10** Timber structures
- **WG 11** Framework of the conservation process

Figure 1.
Organisation of CEN/TC 346 and the working groups: original and new structure from 2012

cultural heritage objects. For movable objects, these may include storage, use (exhibition, study, conservation, restoration etc.) and transport. Objects stored in a good environment could deteriorate if the climate is changed or if they are moved to another climate without appropriate acclimatisation. Poor handling in transit can be detrimental to objects usually stored in a good environment and light-sensitive objects may discolour or fade rapidly if exposed even briefly to intense light or radiation.

The development of European standards for conserving cultural heritage was initiated by the majority of CEN member states[1] in 2004, based on a strategic plan setting out the aims, objectives and remits of a series of working groups (WGs). The structure of the WGs was based on established theory within the field on preventive conservation (Figure 1). As in other standardisation initiatives, first the terminology used had to be developed and agreed. This work was progressed by WG 1. Characterising the materials at risk and their degradation processes, as well as the materials and techniques used to conserve moveable and immovable objects were the remits of WG 2 and WG 3. WG 4 was tasked with developing specifications, measurements and control measures for environmental conditions within museum collections. WG 5 was responsible for formulating criteria for packaging and transporting moveable objects.

The overall objective of the CEN/TC 346 WG4 Environment was to specify environmental conditions for cultural heritage. The specifications were to be based on scientific knowledge and current practice. The working group was mindful that effective long-term conservation requires balance and compromise. The development of any conservation approach is a challenging process, affected by resource limitations, the particular rates of decay of specific materials, the mixed nature of collections, the complexity of composite objects, varied preservation histories and the perceived values of collections. Conservation solutions should be based on a sustainable approach, characterised by interdisciplinary cooperation and consideration for all those who engage with the cultural heritage object.

[1] CEN members are the national standards bodies of Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland and United Kingdom.

In WG 4 Environment, it was found necessary to develop three levels of standards:

- General guidelines and specifications, for example, 'CEN/TC346 15757 Conservation of cultural property: Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials';
- Supporting standards on general issues, such as 'CEN/TC346 PreWI Conservation of cultural property – Integrated Pest Management (IPM)';
- Detailed descriptions of specific issues, for example, 'CEN/TC346 15758 Conservation of cultural property – Procedures and instruments for measuring temperatures of the air and the surfaces of objects'.

Each subject required experts with different backgrounds. The work process had to be productive in order to meet the CEN timeframe of three years from the beginning of a piece of work to publication of a standard. Mindful of these challenges, WG 4 established a number of task groups (TGs) to support the working group members.

Difficulties and challenges in developing standards
Practical difficulties

Overall, this structure proved reasonably productive but there were some weaknesses, in terms of the pace of work and issues around transparency. Some national committees were concerned about a perceived lack of transparency or overview of progress. There were also challenges in engaging the right experts at the right time. One of the basic problems was that experts were not remunerated for this work, so time had to be found between other commitments. There were additional difficulties in funding travel and accommodation for the two annual meetings needed to allow for sufficient progress between sessions while maintaining momentum. Although new technologies offered alternative possibilities for communication (email, Skype, phone meetings and video conferences), face-to-face meetings were usually preferred as the most transparent and productive means of developing the documents, which involved compromise and balance between the diverse backgrounds and experiences of each member state.

Intellectual challenges

Standard development requires the contribution of interdisciplinary knowledge and experience from the many specialised professions involved. In the conservation of moveable and immovable cultural heritage, specialists included conservators, engineers, chemists, architects, curators, art historians, bureaucrats, administrators and educators, amongst others. Practical, theoretical and research-based approaches were contributed from across Europe. Commercial interests were not a major variable in the development process, but they may become an important factor in the future. The variety of specialists involved and the differences between international approaches presented both opportunities and challenges. The diversity created rigor and breadth but also obstructed consensus, engagement and efficiency.

Collaboration within CEN/technical committees

It also became apparent that many of the working groups and technical committees had overlapping remits. As a result experts in CEN/TC 346 working on a standard for exhibition lighting created a joint working group with CEN/TC 169 Light and Lighting to benefit from the expertise of each technical committee and to avoid duplication of work or conflicting recommendations. For future work, relevant existing technical committees should be identified and contacted before a new work item is initiated; in the case of more complex situations, it may be necessary to undertake a feasibility study before new work streams are commenced.

The revised business plan for developing European standards on the conservation of cultural heritage

For the last few years discussion in the working groups, particularly in the CEN/TC346, had been focused on three main challenges. The first was whether it was possible to create an overview of areas that require a standard, and how these areas might be identified. The second question was how new issues or work streams to develop standards should be devised and the third was focused on the process of developing the standards, particularly how to ensure the right experts were involved from the initial stages of work. Essentially, the problem was how to ensure a transparent and efficient process of developing the standards needed by professionals involved in conserving cultural heritage.

As a result of these discussions a new strategy was agreed in June 2012. More working groups have been established, each with a more clearly defined and focused remit. This has simplified the process of appointing relevant experts and will hopefully lead to the more efficient development of standards.

The overall objective of CEN/TC 346 remains the production of standards applicable to the conservation of movable and immovable cultural heritage, in terms of environmental control and interventive conservation.

Table 1. Published and drafted standards related to environmental issues by autumn 2012

EN number	Title	Developed by (until 2012)	Developed by (post 2012)
EN 15757:2010	Conservation of cultural property – Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials	WG4	-
EN 15758:2010	Conservation of cultural property – Procedures and instruments for measuring temperatures of the air and the surfaces of objects	WG4	-
EN 15759-1:2011	Conservation of cultural property – Indoor climate – Part 1: Guidelines for heating churches, chapels and other places of worship	WG4	-
CEN/TC 346 – Environmental standards by autumn 2012 under development			
FprEN 16141	Conservation of cultural property – Guidelines for management of environmental conditions – Open storage facilities: definitions and characteristics of collection centres dedicated to the preservation and management of cultural heritage	WG4	-
FprEN 16242	Conservation of cultural property – Procedures and instruments for measuring humidity in the air and moisture exchange between air and cultural property	WG4	WG7
prEN 15759-2	Conservation of cultural property – Indoor climate – Part 2: Ventilation	WG4	WG7
prEN 16163	Conservation of cultural property – Exhibition lighting of cultural property	WG4	Jointly between TC346 and TC169
prEN 15999-1	Conservation of cultural property – Guidelines for management of environmental conditions – Recommendation for showcases used for exhibition and preservation of cultural heritage – Part 1: General requirements	WG4	WG4
prEN 15999-2	Conservation of cultural property – Guidelines for management of environmental conditions – Recommendation for showcases used for exhibition and preservation of cultural heritage – Part 2: Technical requirements	WG4	WG4
PreWI	Conservation of cultural property – Integrated Pest Management (IPM)	WG4	WG4
PreWI	Conservation of cultural property – New sites and buildings intended for the storage and use of collections	WG4	WG4
PreWI	Conservation of cultural property – Risk assessment methodology for moveable cultural heritage	WG4	WG4
PreWI	Conservation of cultural property – Guidelines for improving energy efficiency of architecturally, culturally or historically valuable buildings	WG4	WG8
PreWI	Conservation of cultural property – Procedures and instruments for measuring moisture content in objects and building materials	WG4	WG7
PreWI	Conservation of cultural heritage – Emergency and contingency plan	-	WG4

11 WGs (replacing the previous five) have been established with more tightly defined mandates than previously (Figure 1). The focus of CEN/TC 346 will be on finishing work in progress. New WGs will be created only when a minimum of five CEN members commit themselves to participate. When work is completed, a WG will be closed. WGs will continue only if CEN/TC 346 considers the same group of experts would be required for developing a new related standard.

The title and objective of WG4 has changed under the new structure; the group has been renamed 'Care of collections' rather than 'Environment' (Figure 2). Four working groups, rather than one, are now responsible for drafting the environmental standards.

The environmental standards and drafts within CEN/TC 346

Table 1 provides an overview of published and draft standards related to environmental control for cultural heritage; it also indicates the WG previously responsible for developing the standards and which team is now accountable under the new strategy.

Discussion

The original approach of WG4 Environment was holistic, focused on drafting documents to cover all aspects of environmental control for cultural heritage, defined as museums, archives and library collections, as well as historic houses and outdoor monuments. Its remit included developing specifications for environmental control and measurement as well as for management and planning issues. Initially, the proposed structure of the standard was a general introductory document followed by supporting notes on specific issues such as climate, air quality, housekeeping, exhibitions, risk assessment and collection management, etc. It was intended that the supporting notes would assist the end-user to achieve the specifications (as set out in the introductory document) through practical step-by-step advice. However, in practice, when the drafting began it proved difficult to reach consensus on either structure or content.

The result was that general introductory documents were prepared for each subject, supported by more specific standards (for example, indoor climate, part 1 and part 2; showcases used for exhibitions, part 1 and 2). Some issues became dormant due to a lack of available experts (e.g., air quality). While the published and draft documents provide good advice and describe relevant approaches, they are not as specific as the end-user might require. Initially a classification system was proposed to specify the quality of the storage environment, for example, 'good', 'better' and 'best'. However, a more descriptive approach was chosen, which established a general direction but did not provide precise step-by-step instructions. While general descriptions can be very informative, it is generally helpful to supplement descriptive documents with more practical information.

A good example of an effective approach is ISO 18934 on archives for imaging materials [7], or the recently published Publicly Available Specification (PAS) 198:2012 [9]. The concise information on environmental issues provided in the main body of these documents is supported by annexes, where more specific

information and the relationship between various risk factors and the stability of materials is presented; a comprehensive bibliography is also included. Both standards reflect new conservation theory by providing guidance on how to establish an environmental specification for a particular collection. They replace the old approach of setting out narrow specifications with tight tolerances, which were often very difficult to achieve and involved high running costs.

A set of good standards for environmental control could assist conservation professionals on a practical level, by providing guidance on how to establish safe environments for museums and archive collections. They could also support conservation management issues, such as negotiating with decision makers for resources. Specifically, there are four main spheres in which they may support conservation work:

1. Help the end-user establish a safe and sustainable environment for a museum collection;
2. Help the end-user secure resources from decision makers by reference to internationally recognised standards for a state-of-the-art environment;
3. Help the end-user specify deliverables from external contractors, taking into account both initial investments and running costs;
4. Help the end-user demonstrate to decision makers through a cost-benefit analysis that a better quality storage environment will increase the expected lifetime of the collection and reduce the running costs.

The published and drafted environmental standards within CEN/TC 346 will help end-users improve the environment around museum collections and increase the expected lifetime of the collections. However, experience suggests they may not yet be sufficiently robust to achieve the other goals set out above. Standards like ISO 18934 and PAS 198:2012 are more appropriate to fulfil the first three goals set out above.

Discussions should continue around developing a certification or accreditation system to document the quality of a museum storage or exhibition environment. An accreditation procedure could improve the development of different technological solutions to build a sustainable museum climate. It could also be a very powerful tool to document the return of investments to decision makers. However, the transaction costs of developing and maintaining such a system must be considered carefully.

Conclusion

My personal experience of using standards on the permanence of photographs and imaging materials has demonstrated how helpful they can be in developing general conservation knowledge and increasing understanding of environmental control principles and practice. The ambition to develop European standards should be recognised as a long-term strategic initiative that will increase the quality of conservation processes and expand the body of conservation knowledge, as well as foster cooperation and synergy between European experts. However, the process of drafting standards is complicated and time-consuming. Rather than seeking consensus on obsolete theories, the ambition must be to achieve standards underpinned by cutting-edge research and practice.

Achieving a set of environmental standards for collections care will extend the usable lifetime of cultural heritage by many decades and reduce the resources and energy required for conservation. Good standards will reduce uncertainties and provide sound guidance for sustainable approaches to the long-term preservation of cultural heritage.

Acknowledgements

References

[1] CEN/TC346, Business Plan, Draft 4 (2012) 5.

[2] Johansen, K.B., and Braae, M., 'Condition assessment for the Danish Film Archive', in Preserve Then Show, ed. D. Nissen, L.R. Larsen, T.C. Christensen, J.S. Johnsen, Danish Film Institute, Copenhagen (2002) 78–93.

[3] Bigourdan, J-L., 'Environmental assessment and condition survey – a strategic preservation plan for DFI's motion picture film collections', in Preserve Then Show, ed. D. Nissen, L.R. Larsen, T.C. Christensen, J.S. Johnsen, Danish Film Institute, Copenhagen (2002) 109.

[4] Johnsen, J.S., 'From condition assessment survey to a new preservation strategy for the Danish film archive', in Preserve Then Show, ed. D. Nissen, L.R. Larsen, T.C. Christensen and J.S. Johnsen, Danish Film Institute, Copenhagen (2002) 115–124.

[5] ISO 10356, 'Cinematography – Storage and handling of nitrate-base motion-picture films'.

[6] ISO 18991, 'Photography - Processed Safety Films – Storage practices'.

[7] ISO 18934, 'Imaging Materials – Multiple media archives – Storage environment'.

[8] Ryhl-Svendsen, M., Klimakontrolstrategi på Nationalmuseet (2012) (unpublished).

[9] PAS 198:2012, 'Specification for managing environmental conditions for cultural collections'.

Author

Jesper Stub Johnsen is Director of Conservation at the National Museum of Denmark (NMD). He is also a member of CEN (European Committee for Standardisation) TC 346 Conservation of Cultural Heritage, and Convener of Working Group 4 on Environment, and International Standard Organisation (ISO) TC42, WG5 on the physical properties and permanence of imaging materials. Email: jesper.stub.johnsen@natmus.dk

Collections demography: stakeholders' views on the lifetime of collections

Catherine Dillon, William Lindsay, Joel Taylor, Kalliopi Fouseki, Nancy Bell and Matija Strlič

Abstract

Recent guidance for British cultural heritage organisations that care for cultural collections recommends that planning of environmental controls should be done within the context of the 'expected collection lifetime', taking into account resources, significance, use and material change. The Collections Demography project is working towards a model of collection change in historic libraries and archives that aims to integrate these variables, and which, therefore, may aid implementation of the new guidance. A key element of the work is an innovative public engagement project that is seeking to engage stakeholders in conversations around the value and lifetime of collections. This paper outlines three aspects of the public engagement programme: interviews with users, a questionnaire survey of users, and workshops. The VALUE (Value and Lifetime – User Engagement) questionnaire is described in detail. In particular, results are presented which are relevant to the development of the Collections Demography model and the implementation of recent guidance. The analysis of the questionnaire provided data on stakeholders' definitions of lifetime and their views on the desired lifetime of collections. The results also indicated that 'context of use' (e.g., the type of institution that holds a collection and the activities that can take place there) is associated with how stakeholders think about the value and lifetime of collections. Such results can inform modelling of collection change by providing justification for the use of particular damage thresholds and by providing a planning horizon over which damage should be assessed.

Background to the Collections Demography project

The Collections Demography project is breaking new ground by exploring parallels between collection modelling and population modelling in the context of historic libraries and archives. An interdisciplinary team has been drawn from the fields of climate science, heritage science, social science, collection management and conservation with the aim of integrating knowledge concerning environmental change, the indoor and outdoor environment, material change and heritage values. The project is working towards an innovative collections management tool that will describe and predict the effects of the environment, material composition and use on the rate of change within collections and the impact of change on collection values.

Collections Demography and standards and guidelines

New British guidance asks organisations to consider the intended lifetime of their collections when making decisions about storage and use (PAS 198 [1]). In particular, the guidance asks that

an organisation's strategy for the preservation of a collection should include a statement of the 'expected collection lifetime'. An organisation should take into account available resources, significance, planned use and display, and the expected rate of deterioration of materials when thinking about expected collection lifetime.

Work to date on the Collections Demography project suggests that an understanding of value is crucial in discussions of collection lifetime. By integrating research into material change with research into what change is considered to be 'unacceptable' (and therefore a loss of value) within the context of a particular collection, projections concerning the future lifetime and value of that collection could be modelled.

Public engagement in the project

A key element of the Collections Demography project is an innovative public engagement programme that is investigating the values stakeholders attach to objects held in particular collections. The programme encourages a conversation between different stakeholders about how to define unacceptable change and think about the desired lifetime of those collections.

This paper describes the public engagement element of the project and how the results may be used to provide context in the development of the collections demography model and inform decision-making using the model. Users of historic archives and libraries have been consulted in a number of settings using a range of methods such as interviewing and questionnaire methods. The results have been used to identify what users think is important about collections and investigate the relationship between those values and attitudes towards the future of collections.

'Value' and 'damage' definitions

Literature reviews were first conducted and have been used to provide a framework for how 'value' and 'damage' are defined and analysed within the project.

- A comprehensive review of the heritage values literature describes the wide-ranging typologies of value that currently exist in the literature and the often conflicting ways in which 'value' is conceptualised and operationalized in collections care and conservation [2].
- Vision and mission statements from project partners and key pieces of policy, such as 'Archives for the 21st Century' [3], were also collated in order to examine how institutions express their aims and the impacts they hope to achieve.
- A review of the literature on discounting and time preferences in decision-making looked at methods of valuation used in the cost benefit analysis of government projects in order to identify parallels in collections management. Methods of valuing decisions made about collections using estimates of lifetime were reviewed and tested [4].

For the purposes of modelling, 'value' has been operationalized in the project in terms of the benefits that can flow from a collection and which are dependent on material change. Benefits can be thought of in terms of both personal significance (the importance

or meaning that users ascribe to or derive from documents) and institutional impact (e.g., an archive providing resources to support government, or a historic house supporting learning by illustrating past use). Such benefits have some dependency on the activities that users can engage in (such as reading for research or viewing documents in exhibitions or on shelves). Without the continued 'health' of a collection such activities and the benefits associated with them may be much reduced. Hence, collection lifetime is used within the project as a proxy for some types of value. Lifetime is the length of time a document remains fit for purpose (e.g., reading or display). 'Damage' is defined as unacceptable change [5], such as change that affects fitness and hence the possibility of a collection being able to yield future benefits in terms of significance and impact.

Qualitative interviews with readers

In many historic archives and libraries, users (e.g., readers or visitors) have direct contact with the collection and are the people most likely to be affected by changes. For this reason, collection values (in terms of personal significance) were first identified at source through interviews with users of The National Archives (UK) original document reading rooms [6]. Interviewees were presented with a document that they were using in their own research and with a document that had been declared 'unfit' for production in the archive. Using an unstructured format, interviewees' narrative responses to the documents were collected and analysed. The interviews were designed to elicit personal and comparative statements of value from readers. Value statements were extracted from interview transcripts and grouped into themes summarising the main content of the narratives. Conservation experts were invited to comment on the coding of the transcripts. The main themes identified were that documents were important to readers:

- For the relationship they offer to the past
- For the relationship they offer with places
- For the understanding they offer
- For the impact on the value of readers
- For the relationships among documents
- For the benefits of access
- For the emotional impact on the reader
- For being.

A further group of statements related to readers' observations of and experiences with the physical object (such as its care, completeness, condition and usability).

Design of an attitudes questionnaire

Value statements taken from the interviews and literature reviews were used to construct an attitudes questionnaire for users of historic libraries and archives. The VALUE questionnaire was designed to collect information about characteristics of the user (e.g.,activities, experience and demographics), a particular document they were using or viewing, what they think is important about the document (i.e., ratings of value statements), their perspective on the desired lifetime of the document and their opinions on the document's condition, care and use. The questions were designed for specific types of multivariate analysis. Versions were created that were suitable for different 'contexts of use':

Table 1. VALUE Questionnaire - distribution and returns

Activity	Venue	Returns by Venue	Returns by Activity	% Total Returns
Reading Rooms (documents handled and read in reading rooms)	The National Archives (UK)	290	393	72 %
	Library of Congress (USA)	103		
Exhibits (documents viewed as exhibits, e.g. under glass)	Capitol Visitor Centre (USA)	43	54	10 %
	The National Archives (UK) Museum	11		
Historic Houses (books viewed on shelves in English Heritage properties)	Brodsworth Hall	31	94	17 %
	Kenwood House	28		
	Eltham Palace	35		
Total			543	100 %

reading documents in a historic library or archive (Reading Rooms), viewing documents as exhibits in a museum or exhibition space (Exhibits) and viewing documents on shelves in historic house libraries (Historic Houses). The analysis described below focuses on a factor analysis of the value statements, a cluster analysis of users (based on extracted factors) and users' attitudes towards the future of documents.

Distribution and returns

'Paper and pencil' questionnaires were distributed face-to-face in reading rooms, exhibition spaces and historic houses. The questionnaire was distributed from September 2011 to January 2012 at a number of venues. Each venue holds collections of documents (mainly paper) but in widely different settings, with different aims and activities. Table 1 shows the number of usable returns per venue and activity. Overall, around half of those approached took a questionnaire and around half of these were returned (giving a good overall return rate of around 25 %).

Key Findings
What is important to users?

Respondents were asked to think about a particular original document they had used (Reading Room) or viewed (Exhibits) that day or about the books in the Historic House library they had viewed. They were asked to think about 'original documents' (objects retrieved from a repository or on display) as opposed to copies (e.g., digital documents). They were given a series of around 60 statements about the importance of the document(s) and asked to rate their agreement/disagreement with each statement. Principal Axis Factoring (a form of exploratory factor analysis) was used to find structure in the ratings of the value statements (i.e.,

subsets of statements that correlated with each other to a higher degree than they correlated with statements in other subsets) [7]. A nine-factor solution was found to be a good fit to the data (56 % of variance explained). The nine-factor solution is summarised in table 2.

The factors are similar to the themes identified during interviews. They relate to both personal significance and the wider impact of historic archives and libraries and so are relevant to both the user experience and institutional aims. The factors were shown to have good reliability (tested using split-half reliability and alpha reliabilities) and were therefore suitable for use as variables in further analysis. The validity of the factors can be demonstrated by comparing value profiles between the different contexts of use in which the questionnaire was distributed. Figure 1 shows that agreement with the importance of Materials & Sensory Experience was stronger for Historic House visitors than other types of respondents, whereas agreement with the importance of Content & Learning was stronger for Readers than for other types of respondents.

What is the 'end of life' for a document?

The questionnaire also included some open-ended questions to probe respondents' definitions of lifetime. Respondents were asked how they would define the 'end of life' for a document/book(s) like the one(s) they had been using/viewing that day. The textual

Table 2. Factor structure of value statements from the VALUE questionnaire

| Factor Name	Description
Future Value	Statements in this factor relate to the potential future value of documents, their significance to society and value to others, altruistic feelings about collections and the survival of documents
Materials & Sensory Experience	Statements relate to users' sensory experience of documents (mainly visual) and refer to such things as style, design and materials
Public Value & Evidence	Statements in this factor were based on a set of statements found on the Public Service Quality Group's biannual survey of UK archives [8]. They were found to cluster together in this factor. Statements refer to some of the core roles of government archives in supporting business, administration and the law
Personal Meaning & Identity	Statements in this factor relate to the way in which original documents may be used in archives and libraries to build understanding of family, community and personal identity, for example by gaining insights into one's personal origins or feeling more connected to other people in the present day
Understanding the Present	Statements refer to the use of documents to help understand events in the present day and to link the past to the present
Discovery & Engagement	Statements in this factor refer to the way in which using or viewing original documents can elicit surprise, feed curiosity and stimulate the senses
Content & Learning	Statements in this factor refer to the information content (i.e., text and images) of documents, what can be learnt from them and their role in enabling understanding of and insight into the past
Connection to the Past	Statements in this factor reflect an interest in what mattered to people in the past, how documents can help the user or viewer feel connected to people in the past, and how documents are part of history
Rarity	A small factor with statements relating to the uniqueness of the document and whether it could be replaced if damaged
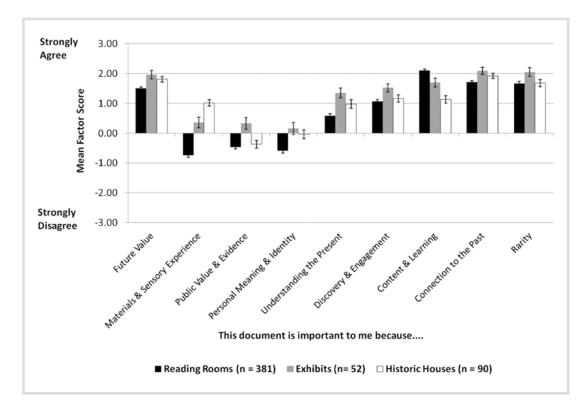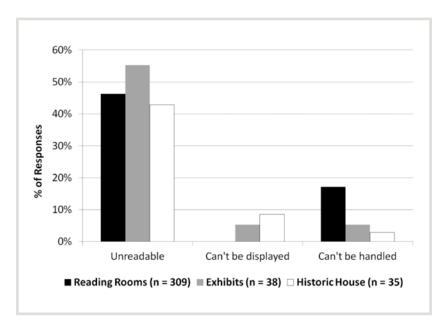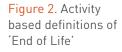
responses were coded so that different types of definitions could be examined in detail. The two most frequent sets of definitions related to the activities that can be performed with a document (57 % of all responses) and descriptions of the physical state of documents (46 % of all responses).

Across all responses, 'end of life' was most commonly defined in terms of not being able to read a document – see figure 2. This is closely related to the intended aim of an archive or library to be a source of information and evidence. Readability was the most frequent definition of 'end of life', regardless of the context of use, although other actions (i.e., display) were mentioned by visitors to Historic houses and viewers of Exhibits (where books cannot be handled). Readers were more likely to mention not being able to handle a document. The results indicate that the lifetime of documents (as an indicator of benefits and value) can perhaps be defined in terms of the primary function of documents (to be read in order to derive information), but that this may vary to some degree according to the way in which a collection is used (e.g., display vs. reading).
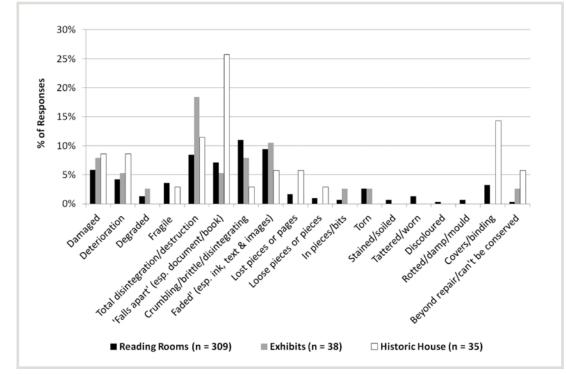
Responses were also coded in terms of 'symptoms' (i.e., features of the physical state of the document, figure 3). In line with the findings above, the symptoms mentioned most frequently were associated with the readability of documents (such as fading, disintegration and falling apart). The context of use may also influence what symptoms are associated with 'end of life'. Visitors to Historic Houses were more likely to mention bindings, covers and documents that 'fall apart' than Readers. These data are descriptive and there were a relatively small number of responses for Exhibits and Historic Houses. In addition, the coding was based on vocabulary: there may be some overlap between coding categories. However, the results are useful in indicating how lifetime might be defined from the user's perspective and how this may vary across contexts.

Figure 2. Activity based definitions of 'End of Life'
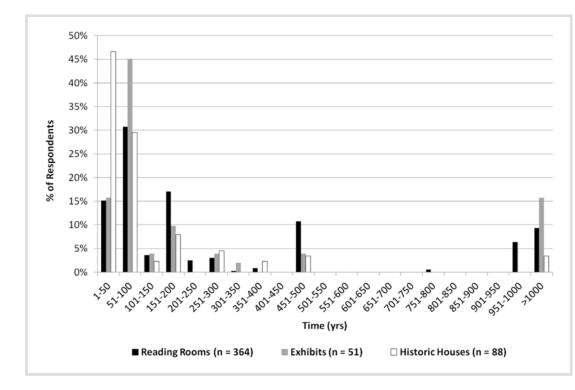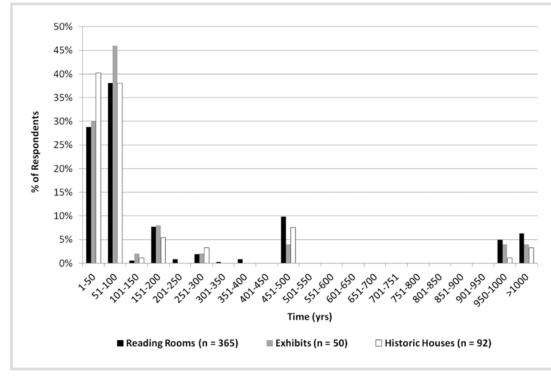
How long should documents be kept in a usable state?

Readers were asked how long they would like the document they had been using to last in a readable state. Visitors to Historic Houses and viewers of Exhibits were asked how long they would like the document(s) they had been viewing to last in a good enough state to be displayed. Figure 4 shows the spread of responses for each context of use. Responses clustered around points in time such as 50, 100, 200 and 500 years, with 86 % of respondents giving a response of 500 years or less. A minority of respondents said that they would like the document to last indefinitely or infinitely (included in the >1000 years group in figure 4). The context of use again appears to be associated with responses, with time perspectives appearing to be shorter amongst visitors to Historic Houses.

Figure 3. Symptoms of 'End of Life'

Figure 4. Frequency of responses to the question 'How long would you like the original document/ books you have been using/viewing today to last in a readable state/a good enough state to be displayed?'
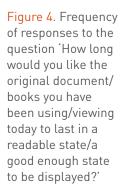
Figure 5. Frequency of responses to the question 'When you think about future generations of readers/visitors, how far into the future are you thinking?'

When is the future?

Respondents were also asked, 'When you think about future generations of readers/visitors, how far into the future are you thinking?'. The most frequent response was 100 years and most respondents gave a response of 500 years or less (Figure 5). Historic House visitors were again shown to have a shorter time perspective than Readers or viewers of Exhibits. A similar question was asked in a previous survey of professionals working with natural history collections [9], which yielded a similar pattern of findings.

What could prevent documents from lasting this long?

Following the question concerning how long respondents would like documents to last in a usable state, they were asked what they thought could prevent documents from lasting this long. This was an open-ended question intended to probe respondents' understanding of causes of unacceptable change in collections (i.e., a shortening of desired lifetime). The results reveal (Figure 6) that, amongst Readers, handling (including general, overuse and misuse) was the most frequently mentioned cause of change. Amongst viewers of Exhibits and visitors to Historic Houses handling was also frequently mentioned. However, environmental conditions and storage (particularly damp, mould and insects) were the most frequently mentioned causes of shortened life for Historic Houses. The results are encouraging from a collections care perspective in that users are aware of the impact of handling. However, the results may also reveal a mismatch between lay and professional understanding of causes of shortened life. For example, a preservation risk assessment at The National Archives (UK) [10] found that incorrect relative humidity was judged by professionals to be the greatest long term risk to the archive. In Historic Houses, library books cannot normally be handled, and so this is unlikely to be the greatest risk.

Characteristics of the document

When people make a decision with a time element (e.g., between outcomes that can occur sooner or later), they are influenced by a number of factors such as perceptions of risk to outcomes occurring in the future, their degree of impatience for outcomes to occur sooner rather than later, estimates of future utility and judgements about the needs of current versus future generations [11]. The analysis of the questionnaire explored some of the variables that might be associated with respondents' answers to questions that probed their time perspectives. There appeared
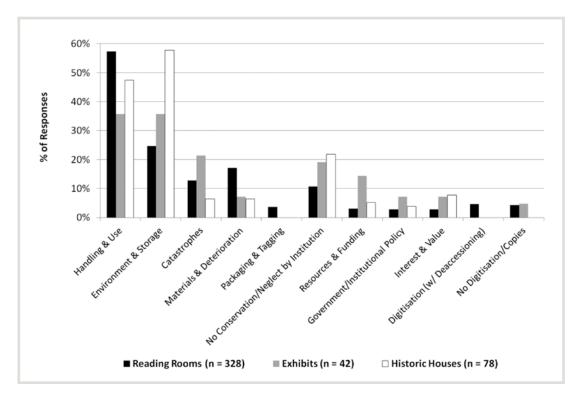
Figure 6. Users' understanding of the causes of reduced lifetime
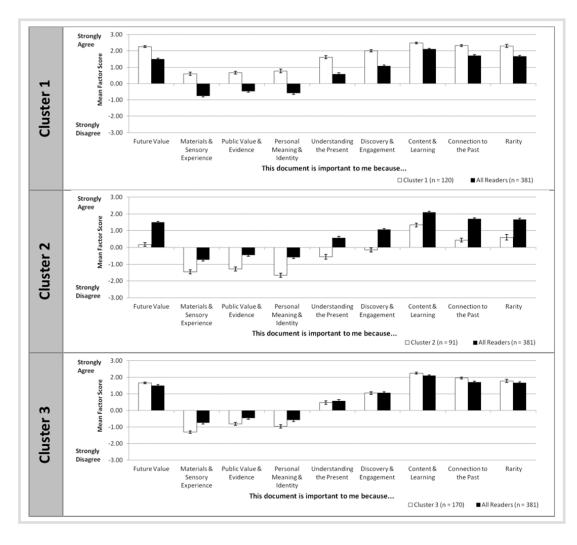
Figure 7. Three clusters of readers that vary according to their value profile

to be a relationship between the age of a document and the desired continued lifetime of a document. Respondents tended to want older documents to last further into the future (there was a statistically significant correlation with a moderate effect size between the two variables, $r = 0.253$, $p < 0.05$). Analysis of comments and other ratings indicated that this finding might be related to the quality of materials of older documents and also the perceived greater historical significance of older documents (and therefore their potential future value).

Attitude profile of the respondent

The results presented above demonstrate that respondents' attitudes towards the future of documents may be related to the context of use and also to the characteristics of documents. Different contexts of use were also associated with different value profiles. To investigate further whether value profiles were associated with variations in attitudes towards the care, condition and use of documents a cluster analysis (Ward's method) was conducted, to find groups of respondents with similar ratings on each of the nine value factors. Within Readers, three distinct clusters were found and their value profiles are shown in figure 7.

Clusters varied not only according to their value profile but also according to other variables. For example, Readers in Cluster 1 tended to have a positive score on all factors. Personal/leisure readers (including respondents who were researching family

history) were more likely to be in this cluster than other clusters. Cluster 2 tended to disagree with or be neutral about each factor except 'Content & Learning'. Readers who were visiting an archive or library for work in connection with employment were most likely to be in this cluster. The clusters perhaps represent different types of audiences who use original documents in reading rooms, and it is likely that other attitude profiles would be found if other groups of stakeholders were also included (e.g., users of digital documents or professionals involved in the care and management of collections).

A second factor analysis was conducted on a second set of rated statements on the questionnaire that queried respondent's attitudes towards the care, condition and use of original documents. Each of the three clusters of Readers shown above was then compared on this second set of six factors. The results are shown in figure 8. Each of the new six factors has been labelled using a single statement summarising the group of statements in the factor. The analysis appears to suggest that different communities of readers have different attitudes towards documents. For example, Cluster 1 appears to have a greater focus on the need to use original documents than other clusters.

Using the findings

The findings of the questionnaire study are relevant to the development of the Collections Demography model and the implementation of PAS 198 in a numbers of ways. In particular, the results can help set damage thresholds and appropriate planning horizons for modelling.

Firstly, the results illustrate what is important to users about their contact with collections and how this can vary according to different contexts of use. For example, information content was
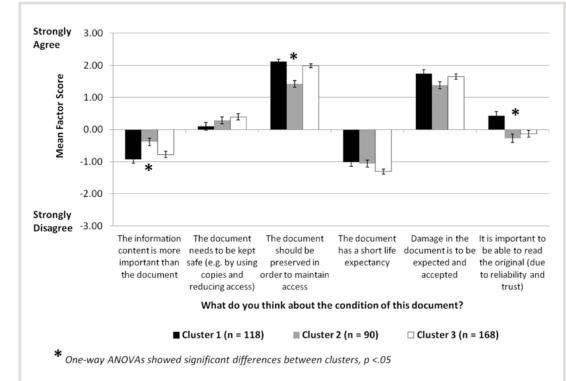

Figure 8. Attitudes towards the care, condition and use of original documents for the three clusters of readers

shown to be more important to Readers than other groups of respondents, whereas materials and the sensory experience of documents were more important to visitors to Historic Houses than other groups of respondents. The results indicate that context will have a relationship with what characteristics of a collection (e.g., information vs. materials) are considered most important to preserve and therefore how lifetime should be defined for different contexts of use.

Secondly, it was shown that there may be a relationship between context of use and attitudes towards the future. Shorter time perspectives were found amongst visitors to Historic Houses (where books can be displayed but not read) in comparison to Readers and visitors viewing Exhibits. The questionnaire responses provide a planning horizon over which to model material change and assess the impact of environmental controls in different contexts. The long-term perspectives found in most users' responses (100–500 years) have some parallels with time perspectives used in environmental economics, where it has been proposed that the long-term consequences of resource loss and carbon reduction should not be masked by high discount rates and short planning horizons [12].

The questionnaire results also provide a definition of the 'end of life' of documents from the user's perspective. Not being able to read a document appeared to be the defining characteristic of 'end of life' across all contexts of use (with some variation). This definition fits neatly with the intended aims of archives in particular, which provide original documents for use in primary research. When modelling material change over a given planning horizon this definition provides justification that any changes which affect fitness for purpose (reading or display, depending on the context) can be used to set a damage threshold and predict end of life (and therefore loss of collection benefits or value).

The results also demonstrate how biases could occur when using stakeholders' views directly in modelling. For example, users show a high level of awareness of handling as a cause of shortened life. However, this may contrast with professional judgements of the greatest long terms risks for some institutions (e.g., change across large archive collections due to environmental conditions, rather than single instances of damage due to handling). Furthermore, the results also suggest that attitudes towards the future may vary according to such factors as the characteristics of a document (e.g., age and perceived significance), which in turn suggests that attitudes are likely to change over time as collections and their use change. In addition, different communities of stakeholders may have different attitudes towards the future care, condition and use of documents. Understanding potential sources of conflict and bias such as these may help to inform how the results of engagement with different groups of stakeholders are interpreted and used.

Next steps

Findings from the questionnaire study are being used to inform the design of workshops with stakeholders. Where the questionnaire sought diverse opinions in response to diverse documents in order to start to build a picture of the relationship between what is important to users and their attitudes towards the future of collections, the workshops will investigate similar questions but

under more controlled conditions. Workshop participants will be presented with sets of documents that have been degraded along known parameters and asked to rate fitness for different purposes (e.g., reading vs. display). In addition, participants will be presented with different value scenarios (based on the factor and cluster analysis of the questionnaire) before they make their fitness judgements. In this way, the effects of different contexts of use and value on damage thresholds can be examined and taken into account when using the thresholds in a model of collection change.

Acknowledgements

References

[1] British Standards Institute, PAS 198: 2012 Specifications for Managing Environmental Conditions for Cultural Collections, BSI, London (2012).

[2] Lindsay, W., 'Conceptions and Misconceptions of Value in Cultural Heritage Preservation', Collections Demography Project Report, The National Archives of the UK (TNA), Kew (2012) (unpublished).

[3] HM Government, Archives for the 21st Century, The Stationery Office, London (2009).

[4] Dillon, C., Taylor, J., Lindsay, W., and Strlič, M., 'Implicit and explicit time preferences in collections care and conservation', http://www.ucl.ac.uk/iaq2012/documents/IAQ2012_Book_of_Abstracts_on-line.pdf (accessed 3 August 2012).

[5] Strlič, M., Thickett, D., Taylor, J., and Cassar, M., 'Damage functions in heritage science', Studies in Conservation (forthcoming).

[6] Lindsay, W., 'Speaking their Minds: Archive Users' Values', Collections Demography Project Report, The National Archives of the UK (TNA), Kew (2012) (unpublished).

[7] Tabachnik, B., and Fidell, L.S., Using Multivariate Statistics, 5th edn, Allyn and Bacon, Boston (2007).

[8] Public Services Quality Group of the National Council on Archives, Survey of Visitors to UK Archives 2009: National Report, CIPFA Social Research, Croydon, London (2009).

[9] Lindsay, W., 'Time perspectives: what "the future" means to museum professionals in collections-care', The Conservator 29 (2005) 51–61.

[10] Bülow, A.E., 'Collection management using preservation risk assessment', Journal of the Institute of Conservation 33 (2010) 65–78.

[11] Frederick, S., Loewenstein, G., and O'Donoghue, T., 'Time discounting and time preference: A critical review', Journal of Economic Literature 40 (2002) 351–401.

[12] Stern, N., Stern Review on the Economics of Climate Change, London, HM Treasury (2006).

Authors

Catherine Dillon is a post-doctoral research associate (AHRC & EPSRC Science and Heritage Programme) at University College London, Centre for Sustainable Heritage. Email: catherine.dillon@ucl.ac.uk

William Lindsay was a post-doctoral research associate (AHRC & EPSRC Science and Heritage Programme) at The National Archives (UK) working on the Collections Demography project there until August 2012. He was previously Head of the RCA/V&A Conservation Department at the Royal College of Art. Email: williamlindsay@btinternet.com

Joel Taylor is a researcher at the Norwegian Institute for Cultural Heritage Research (NIKU). Email: joel.taylor@niku.no

Kalliopi Fouseki is the course-director of the MSc in Sustainable Heritage at the UCL Centre for Sustainable Heritage. Email: kalliopi.fouseki@ucl.ac.uk

Nancy Bell is Head of Collection Care for The National Archives. Email: nancy.bell@nationalarchives.gsi.gov.uk

Matija Strlič is Principal Investigator on the Collections Demography Project. He is Senior Lecturer and a Course Director (MRes Heritage Science) at the UCL Centre for Sustainable Heritage. Email: m.strlic@ucl.ac.uk

Licence

The limits of Garry Thomson's Museums Temperate Zone: can they be enlarged?

Luis Efrem Elias Casanovas, Vasco Peixoto de Freitas,
Cláudia Ferreira and Sílvia Oliveira Sequeira

Abstract

In The Museum Environment Garry Thomson wrote: 'Is there such a climate as a Museum Temperate Zone, where throughout the year average daily RH remains within the moderately safe limits of 40 to 70 % and heating is rarely required? There are a few such favoured places scattered along the Mediterranean littoral'. In this study we show that, although Portugal is not typically Mediterranean, we can achieve 'the moderately safe' values quoted by Thomson due to a delicate balance between the outside conditions, the building, and the collections as 'timber old and new will be seasoned to the average prevailing humidity' [1]. The behaviour of Portuguese traditional masonry buildings is well adapted to the climate as demonstrated not only near the coast, but also in Elvas, close to the Spanish border, Évora, Castelo Branco and in Madeira and, most importantly, in the Mafra National Palace built in the seventeenth century, which 'takes six months for cooling and another six months to recover' [2]. Research on hygroscopic inertia processes has enabled us to interpret environmental data, primarily from archives where relative humidity fluctuations are within a 3 % range annually without any mechanical environmental control measures. It seems that by selecting adequate materials together with intelligence of the building and its operators, very little equipment will be required; a truly sustainable approach to environmental control. When briefing architects, we usually begin by emphasising that in Portuguese museums there are problems which will either solved by the architect or they will never be solved.

Introduction

The Museum Environment [1] was considered a difficult text by some though for others it was the Bible of preventive conservation; Garry Thomson did not accept these judgements. In our opinion, the work of Garry Thomson was not discussed and analysed as it deserved. Sarah Staniforth wrote: 'In the late twentieth century the methods used to create benign environmental conditions become increasingly energy intensive, and the drive towards ever tighter standards in museums across the world, regardless of the climate in which a museum is located, caused Garry Thomson to write in the final chapter on 'Future Trends' of his 1978 book The Museum Environment these words: "There is something inelegant in the mass of energy-consuming machinery needed at present to maintain constant RH and illuminance, something inappropriate in an expense which is beyond most of the world's museums. Thus the trend must be towards simplicity, reliability and cheapness. We cannot, of course, prophesy what will be developed, but I should guess that it will include means for stabilising the RH in show cases without machinery, use of solar energy for RH control in the tropics, improved building construction to reduce energy losses and extensive electronic monitoring"'[3]. In fact, in the first pages of his book,

Thomson insists on the importance of the physical reality enveloping the collection and stresses that climate control is only part of the preventive medicine of conservation [1].

Considering that there are sufficient examples to warrant a simple examination of climate zones, Thomson adds: 'Our primary measuring rod is average indoor relative humidity and our chief secondary concern is whether the climate is cool enough for winter heating to be widely practiced'. He goes on to ask: 'Is there such a climate as a Museum Temperate Zone, where throughout the year average daily RH remains within the moderately safe limits of 40 to 70 % and heating is rarely required? There are a few such favoured places scattered along the Mediterranean littoral'.

The Museum Temperate Zone as a sustainability guideline

Garry Thomson's 1978 question has not remained unanswered: aware that 'there are a few such favoured places', we want to find out if it is possible to apply the same methods to control the environment irrespective of what zone the museum is in. During the last decade,

Table 1. Materials discussed in figure 1 [6]

Reference	Base material	Acrylic primer	Finishing paint
GC	Gypsum Board (12.5 mm)	–	–
GC2	Gypsum Board (12.5 mm)	–	Vinyl – 50 µm (2 layer)
GC2A	Gypsum Board (12.5 mm)	25 µm (1 layer)	Vinyl – 50 µm (2 layer)
GC3	Gypsum Board (12.5 mm)	–	Acrylic – 50 µm (2 layer)
GC3A	Gypsum Board (12.5 mm)	25 µm (1 layer)	Acrylic – 50 µm (2 layer)
GP	Gypsum Plaster (11 mm)	–	–
GP2	Gypsum Plaster (11 mm)	–	Vinyl – 50 µm (2 layer)
GP2A	Gypsum Plaster (11 mm)	25 µm (1 layer)	Vinyl – 50 µm (2 layer)
GP3	Gypsum Plaster (11 mm)	–	Acrylic – 50 µm (2 layer)
GP3A	Gypsum Plaster (11 mm)	25 µm (1 layer)	Acrylic – 50 µm (2 layer)
GT	Gypsum + Lime Plaster (10 mm)	–	–
GT2	Gypsum + Lime Plaster (10 mm)	–	Vinyl – 50 µm (2 layer)
GT2A	Gypsum + Lime Plaster (10 mm)	25 µm (1 layer)	Vinyl – 50 µm (2 layer)
GT3	Gypsum + Lime Plaster (10 mm)	–	Acrylic – 50 µm (2 layer)
GT3A	Gypsum + Lime Plaster (10 mm)	25 µm (1 layer)	Acrylic – 50 µm (2 layer)
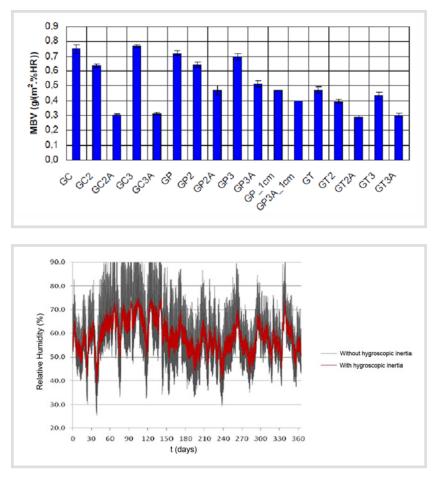
developments in building methods and materials have begun to enable more sustainable control of the museum environment. The Portuguese climate is particularly well suited to help us answer this question because of its location and unique status within the Iberian Peninsula [4].

Hygroscopic inertia: the concept

Hygroscopic inertia refers to the capacity of a building or compartment to reduce peaks of relative humidity naturally by storing excess moisture and restoring it to the atmosphere when the humidity is low. Rendering and coating materials are largely responsible for this mechanism. Hygroscopic inertia may be assessed over short periods of time (short-cycle hygroscopic inertia of compartments) and for longer periods of time (long-cycle hygroscopic inertia of compartments).

Studies have shown that, in museums located in old buildings in temperate/ Mediterranean climate zones with strong thermal inertia and poor ventilation (relative to the volume and number of visitors), hygroscopic inertia contributes effectively to the maintenance of ideal conservation conditions, thereby dispensing with the need for complex active systems.

Within the NORDTEST [5] research project, a test procedure was developed to define the moisture storage capacity of building materials through a property to be determined experimentally. This gave rise to the concept of Moisture Buffer Value (MBV). The MBV indicates the amount of moisture transported to or from a building material during a daily cycle (short cycle), relative to the unit of area

exposed to an atmosphere with cyclical variations in humidity. It may be determined for homogeneous materials or compound elements in contact with the indoor atmosphere. It is calculated by placing the material in a climate chamber with daily cyclical variations in relative humidity, and recording the variations in mass. The MBV results from the difference between the maximum and minimum values in the mass variations in the stable cycle (Figure 1).

In Portugal, at the Building Physics Laboratory in the Faculty of Engineering, University of Oporto, dynamic hygrothermal simulation programmes and experimental studies have shown that reductions in peaks of relative humidity are related to the hygroscopic materials applied and to the size of the surface area [6, 7] (Figure 2).

Museum environmental control in Portugal

Central heating was not common in Portugal until the first decades of the twentieth century. The first museums to have heating and ventilation were the Museu Nacional de Arte Antiga in Lisbon and the Museu Nacional de Soares dos Reis in Oporto, both in 1940. In 1983, the Tile Museum in Lisbon, housed in the sixteenth-century Convento da Madre de Deus, was renovated for the seventeenth Exhibition of the European Council. For reasons of economy, full air conditioning was not installed, but as the forecast (and actual) number of visitors per day was 3000, a simple system of temperature-controlled ventilation was installed, involving no recirculation and with supply air temperature kept at 21 to 22 ºC. Thermo-hygrograph charts show that room temperature was below 23 ºC and RH was at 55, plus or minus 5 % without humidifying equipment [8]. Despite several years of thermo-hygrograph charts and data on external conditions, the officials responsible for reviewing heating, ventilation and air conditioning (HVAC) regulations continued to search for ideal conditions, disregarding contemporary conservation opinion that the importance of RH fluctuations had been overstated and that 'safe RH is a broad valley ...' [9].

Further examples became available for our research [10] and in 1999, for the ICOM-CC 12th Triennial Meeting in Lyon, we presented with Ana Isabel Seruya a case study of climate control in a sixteenth-century building in Évora, in the south of Portugal [11]. The final result was the same as in the Tile Museum in Lisbon, although Évora is 120 km away from the coast. As we had only one building to work with in each case and no historical data, we did not consider the possibility of extending the method to other museums or areas. Some years later in 2004 it was decided to move the archives of the Santa Casa da Misericórdia de Lisboa, a welfare institution founded in August 1498, from an apartment building in the centre of Lisbon to the seventeenth-century Palácio Nisa[1]. Having tested the Palácio's thermal characteristics, it was agreed not to install air conditioning but to rely on the usual behaviour of the classic Portuguese masonry; the conditions were well within the 'proofed fluctuation' of the previous 40 years, i.e., 40 to 75 % RH and 16 to 26 ºC. Some of the results can be found in the 52 thermo-hygrograph charts (from to March 2011 to April 2012), which can be downloaded as an interactive pdf file from [12]. Four example charts (one from each season) are shown in figures 3 to 6. In January 2010, in this same archive, due to a water infiltration

[1] The Palace was demolished before the earthquake of 1755 but was rebuilt and repaired. It kept the name because the first owner was a descendent of Vasco da Gama.

in the exterior wall of a subterranean archival room, fungal development occurred in documents located on bookshelves near this wall. The fungi developed only in some of the coated paper file covers located on the lower shelves. Nevertheless, the RH levels registered by the thermo-hygrograph remained below 60 % (Figure 7 and 8), since the equipment was located in the middle of the room and not near that wall. This is an example of how essential periodic visual inspection of collections is, regardless of
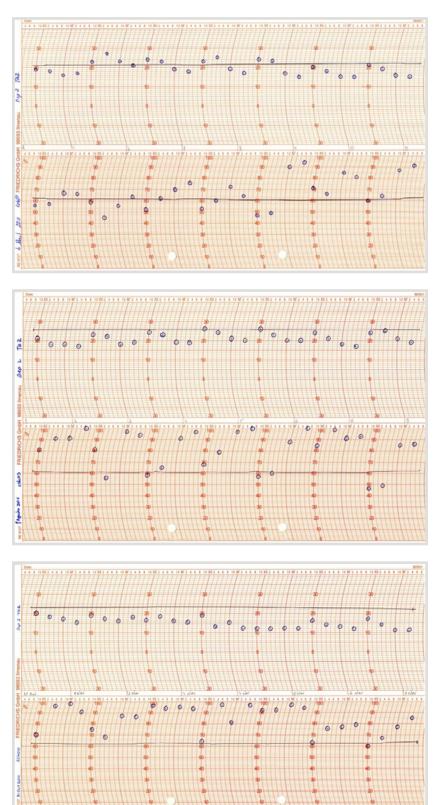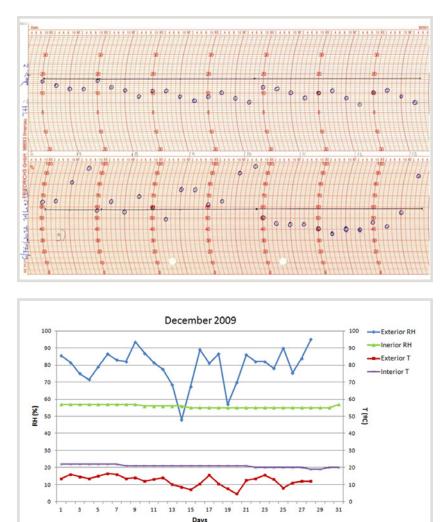
Figure 3. Thermo-hygrograph chart (the dots represent the exterior conditions) from the archival storage room #2 in Santa Casa da Misericórdia de Lisboa recorded between 4–11 April 2011 (Spring)

Figure 4. As figure 3 recorded between 1–8 August 2011 (Summer)

Figure 5. As figure 3 recorded between 31 October– 7 November 2011 (Autumn)

Figures 7 and 8. Average RH and T values outside and inside the archival room where fungal growth was detected, on December 2009 and January 2010, respectively

environmental monitoring equipment (as it is not possible to have measuring probes in every corner) whether using HVAC systems or passive control systems, as in this case.

After detecting the infiltration source and amending the problem, the air circulation was improved with strategically located simple domestic fans. This measure helps to homogenise the temperature and relative humidity on the surface of the documents, preventing microclimates with higher water availability forming, which are prone to fungal development.

Portuguese climate and the way to sustainability

Michalski wrote that 'By the 1960s and 1970s, designers worldwide demanded specifications by which to build. The familiar numbers, 50 % or 55 % RH, emerged from many experts, but actual knowledge about humidity had not changed in 100 years' [9]. This knowledge has now changed and we now know that the environmental parameters in a museum must be established in accordance with the collection, the building, and the local climate rather than according to some unrealistic figures like the famous 60/60 rule [13]. In Portugal it appears that it is comparatively easy to achieve such a balance, provided the building is well managed. As Tim Padfield wrote, 'Portugal is blessed with a perpetual moderate climate so should have no trouble preserving its relics' [14].

In fact Spanish geographers have defined a special type of Iberian climate which they called 'clima Português' i.e., 'Portuguese climate' [4] because it is different from the Spanish climate: the winter is less cold and the summer less warm, which means that the dangerous extremes are less dangerous. As Juan Vilá Valenti wrote 'Nos referimos pues a lo que podemos llamar disimetria del clima en las dos frentes costeros peninsulares lo qual representará evidentemente una clara personalidad climática del conjunto de Portugal' [4], or in English, 'We refer to what we can call climate asymmetry in the two peninsular coastal fronts, which clearly represents a distinct personality of the Portuguese climate'. Orlando Ribeiro adds '… along the Iberian Atlantic coast, the Mediterranean characteristics lose their influence under the humid and tepid pressure of the Atlantic breathing' [15].

Concluding remarks

The main conclusions of this paper are:

- In the Portuguese climate it will be possible to control the fluctuation of relative humidity without complex mechanical systems;
- Hygroscopic inertia is an important concept and it is necessary to transfer this knowledge to conservation practice.

Acknowledgements

References

[1] Thomson, G., The Museum Environment, Butterworth-Heinemann, London (1986).

[2] Casanovas, L.E.E., 'Análise da evolução anual das condições ambiente na Biblioteca do Palácio Nacional de Mafra - Algumas interrogações', in I Semana dos Arquivos, ed. M. Cardoso, Instituto Português do Património, Cascais (1986) 67–72.

[3] Staniforth, S., 'Slow conservation', Studies in Conservation, 55.2 (2010) 74–80.

[4] Valentí, J.V., La Península Ibérica, Ediciones Ariel, Barcelona (1968).

[5] Rode, C. (ed.), Moisture Buffering of Building Materials, Department of Civil Engineering, Technical University of Denmark, Denmark (2005).

[6] Ramos, N., A importância da inércia higroscópica no comportamento higrotérmico dos edifícios, PhD dissertation, Faculty of Engineering, University of Porto (2007) (unpublished).

[7] Moura, I.M., A importância dos revestimentos interiores no controlo da humidade relativa interior, Masters dissertation, Faculty of Engineering, University of Porto (2009) (unpublished).

[8] Casanovas, L.E.E. and Freitas, V., 'The way to sustainability; the balance between outdoor climate and natural indoor climate', paper presented to Going Green: towards sustainability in conservation, a conference at the British Museum, London (2009).

[9] Michalski, S., 'Relative humidity: a discussion of correct/incorrect values', in ICOM Committee for Conservation 10th triennial meeting: Washington, DC, 22–27 August 1993: preprints, ed. J. Bridgland, ICOM-CC, Paris (1993) 624–629.

[10] Casanovas, L.E.E., Conservação Preventiva e Preservação das Obras de Arte, Santa Casa da Misericórdia, Lisboa (2008).

[11] Casanovas, L.E.E. and Seruya, A., 'Climate Control in a sixteenth-century building in the South of Portugal', in 12th triennial meeting, Lyon, 29 August–3 September 1999: preprints (ICOM Committee for Conservation), ed. J. Bridgland, Earthscan, Oxford (1999) 27–30.

[12] https://docs.google.com/open?id=0B2O1geQhQBM0b1MyN094UWR6WUU

[13] Oddy, A.,'The three wise men and the 60/60 rule', British Museum Occasional Paper 145 (2001) 167–170.

[14] Padfield, T., freelance consultant in preventive conservation, personal communication, 20 January 2008 (sent to Luis Efrem Elias Casanovas).

[15] Ribeiro, O., Portugal, O Mediterrâneo e o Atlântico: estudo geográfico, Coimbra Editora, Lda., Coimbra (1945).

Authors

Luís Elias Casanovas was awarded a Fellowship from the Foundation for Science and Technology to develop his work on the museum environment of Portuguese Museums and Historic Buildings in 2008. Email: luiscasanovas@mail.telepac.pt

Vasco Peixoto de Freitas is Full Professor of Building Physics (Civil Engineering Department at the Faculty of Engineering – Porto University), Head of the Building Physics Laboratory, Coordinator of the commission CIB W040 – Heat and Moisture Transfer in

Buildings and commission CIB W086 – Building Pathology. He is also a consultant in building pathology and rehabilitation.
Email: vpfreita@fe.up.pt

Cláudia Ferreira is a civil engineer and PhD student at the Faculty of Engineering, University of Oporto, where she develops research about the importance of hygroscopic inertia in museums.
Email: cmiranda@fe.up.pt

Sílvia Sequeira is currently a PhD student in paper conservation at the Department of Conservation and Restoration in the New University of Lisbon. When she participated in this study, she was a science and technology fellow in the Tropical Research Institute (IICT). Email: s.o.sequeira@gmail.com

Acoustic emission monitoring: on the path to rational strategies for collection care

Michał Łukomski, Janusz Czop, Marcin Strojecki and
Łukasz Bratasz

Abstract

This paper reports a cost analysis of various climatic control
strategies in the galleries of the National Museum in Krakow,
Poland based on direct monitoring of the energy consumption
and computer modelling using the WUFI Plus software. The
effectiveness of the existing climate control is also evaluated by
long-term acoustic emission monitoring of an eighteenth-century
wardrobe exhibited in the museum's gallery of decorative art. The
technique allowed the progress of damage to be directly traced and
the risk to be classified from various RH variations. The outcome of
both investigations has supported a review of the museum's policy
and practice on climate control. The modified approach to climate
control was first applied in 2010 during comprehensive rebuilding
and renovation of the historic seat of the Princes Czartoryski
Museum in Krakow.

Introduction

Designing and implementing optimal climate control strategies
in museums is a challenging task due to the conflicting demands
between maintaining high standards of collection care and
the requirement to reduce energy costs and CO_2 emissions.
There has been growing agreement that collections can sustain
greater variations in relative humidity (RH) and temperature than
previously recommended [1], which allows relaxing some of the
controls of the heating, ventilation and air-conditioning (HVAC)
systems and, consequently, reducing the energy consumption
considerably [2]. However, broadening the allowable variations of
climatic parameters has to be informed by a sound understanding
of how changes in climate conditions affect real artefacts.

There are two fundamental approaches to establishing the
allowable ranges of climatic variations for objects that are sensitive
to climate-induced damage: an analysis of the object's mechanical
response to climate variations [3-5], or an analysis of the historic
climate [6] to which the object has become acclimatised.
Both approaches to predicting the risk of damage to a real historic
object in its specific environment can be supported by non-invasive
scientific methods of directly tracing damage, which are capable of
operating in real-world conditions in museums, historic buildings
or during the transportation of works of art. The acoustic emission
method, which is based on monitoring the energy released as
sound waves during fracture processes in materials, has been
particularly successful in directly tracing the fracturing intensity in
wooden objects exposed to variations in temperature and RH [7].

This study provides a comprehensive cost analysis of various
climate control strategies in the galleries of the National
Museum in Krakow (MNK), based on direct monitoring of the

energy consumption and computer modelling using the WUFI Plus software. At the same time, a long-term acoustic emission monitoring project is reported, which evaluated the effect of the existing climate control strategies on an eighteenth-century wardrobe exhibited in the museum's gallery of decorative art. The analysis focused particularly on insufficient humidification during repeated drops in the indoor RH during winter. Already considerably cracked, the wardrobe was selected by the curators as representative of the massive furniture displayed in the gallery and also on account of its particular vulnerability to climate-induced damage.

The outcome of both investigations has supported the development of an effective and economic HVAC system for the historic building of the Princes Czartoryski Museum in Krakow, which is currently undergoing major rebuilding and renovation.

Monitoring energy consumption

The main building of MNK was chosen as a site for a detailed analysis of the energy consumption of systems of climate control operating in the museum. The total surface area of air-conditioned zones in the building is 19500 m^2. The building houses permanent and temporary exhibitions but also the library, offices of museum's administration as well as some of its conservation studios and workshops. The climate control algorithm in the exhibition space followed the institutional indoor climate guidelines, which required a stable RH in the range of 45 to 60 % and a stable temperature in the range 19 to 21 °C dictated by the comfort of visitors and staff. The monitoring has shown, however, that the climatic conditions in the galleries deviate from these guidelines. RH drops below 30 % during cold periods in winter due to insufficient air humidification, which is a typical situation for many museums in central and northern Europe.

Actual power consumption in real time by every subsystem of the HVAC operating in the building was monitored. The total energy consumption in 2010 was 4150000 kWh at 250000 Euro with 64 % on heating for comfort and the remaining 36 % on climate control for conservation. Importantly, 32 % of the total expenditure was spent on drying the air in summer whereas only 4 %, that is eight times less, on humidifying the air in winter. The average ventilation rate in the building was 0.7 air exchanges per hour.

In the next step of the project, computer modelling was used to simulate energy consumption under various climate control scenarios. The accuracy of modelling was verified by comparing the calculated values with those measured during the monitoring described above. The comparison allowed the predictive power of the modelling to be assessed with precision, as the monitoring provided costs of various individual technological processes into which climate control by the overarching HVAC systems operating in the building can be divided.

Modelling energy consumption

Calculations of the energy needed to implement various climate control scenarios were performed using WUFI Plus software calculating coupled heat and moisture transfer in multi-layer building components exposed to the outdoor climate. This method

of calculation is presented elsewhere [8]. The construction of the building and the materials used were taken into account, as well as heat and moisture gains from people working in the building and visiting it. The latter number was through the number of tickets sold during 2010. The model is capable of calculating energy demand for keeping predefined climatic conditions inside the building. The real energy demand was calculated by taking into account the efficiency of HVAC subsystems used for heating, humidifying and drying.

Several climate control scenarios were considered. Three different bands of allowable RH variations were analysed, namely: 45 to 60 % RH, 35 to 60 % RH, and 35 to 65 % RH for various ventilation rates in the building: 0.4, 1.2 and 2.5 air exchanges per hour. The exchange rate of 0.7 per hour measured in the building was also considered in the simulations. The results are presented in figure 1.

The total difference between measured and calculated energy does not exceeds 6 %, whereas the biggest discrepancy (up to 20 %) is obtained for air-drying, the most complex technological process. As expected, the cost of humidifying air increases when the lower RH stabilisation level is raised from 35 to 45 % RH, whereas the cost of drying air increases when the upper RH stabilisation level goes down from 65 to 60 % RH. Further, a strong correlation is observed between the energy consumption and the air exchange rate for all analysed RH ranges. The cost of heating for comfort does not depend on the allowable RH band selected but increases significantly with increasing ventilation rate. The economic benefits from various modifications of the current climate control strategy in the building, that is keeping RH in the range of 45 to 60 % at the ventilation rate of 0.7, are summarised in figure 2. The allowable temperature band is kept unchanged in the climate control modifications considered.

The first possible modification of the current guidelines is an extension of the allowable RH range from 45 to 60 % up to 35 to 65 % RH. The modification results in a reduction of the total yearly energy demand by 13 %, mostly due to the diminished air-drying in summer. The second possible modification is a reduction of
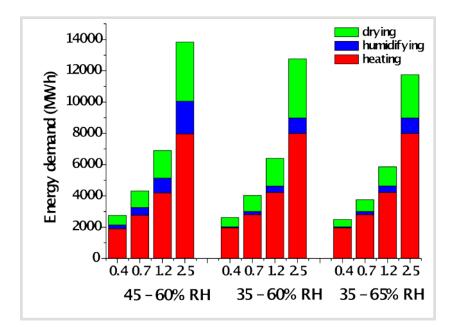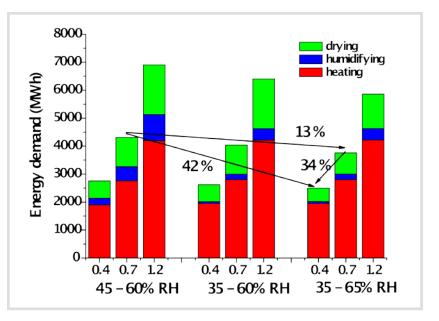
Figure 1. Yearly energy demand for different climate control scenarios in the main building of the National Museum in Krakow. Results for three different allowable bands of RH variations at four air exchange rates in the building are presented
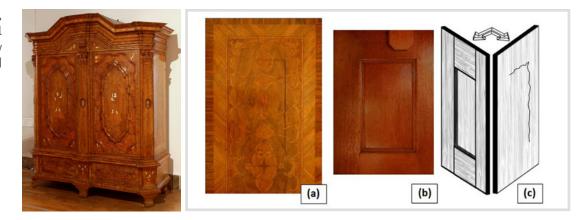
the ventilation rate from 0.7 to 0.4 exchanges per hour by limiting mechanical ventilation of the building. This modification would result in a further reduction of the energy demand by 34 %. Hence, the total energy savings obtained by the above modifications of the allowable RH band and the ventilation rate would be 42 %. Energy savings in other possible scenarios can be analysed from the data shown in figure 2.

However, to let conservation and collection care managers make such decisions, the risk of damage to the vulnerable objects exhibited should be assessed as precisely as possible for various climate control scenarios. Long-term acoustic emission monitoring was used to directly trace physical damage in an eighteenth-century wardrobe exhibited in the museum's gallery of decorative art so that risks to the object from various RH variations could be classified. The measuring technique and the results of the monitoring, which ran for more than two years, are presented below.

On-site acoustic emission monitoring

Acoustic emission (AE) is defined as the energy released due to micro-displacements in a structure undergoing a deformation. The energy passes through the material as ultrasound and sound waves, and is detected on the surface using a piezoelectric transducer, which converts the surface vibration to an electrical signal. The AE experimental setup and details about the data processing and analysis are published elsewhere [9]. Raw data recorded during the monitoring were post-processed with the help of a computer program, which searched for individual AE events, extracted them and calculated the most important AE features, that is, amplitude, energy, duration and frequency distribution.

A wardrobe dated to 1785 was chosen for the AE monitoring as it was representative of the massive furniture displayed in the decorative art gallery of the National Museum in Krakow, and also vulnerable to climate-induced damage. The wardrobe is richly decorated with ornamental carving and a work of supreme craftsmanship. The oak structure is entirely veneered with walnut and decorated with inlays of ivory, tin, graphite and various types of wood in which the maker created rich ornaments including

allegorical figures (Figure 3). Fluctuations in ambient RH are considered to be one of the main factors, which contributed to the past deterioration of the wardrobe. They have caused cracks on the front and side walls in the areas where cross-grained wooden elements were assembled in the structure; the four-part frame has acted as a restraint for the central plank as illustrated in figure 4.

From a technical point of view, long-term, continuous monitoring of the micro-damage development in an object displayed on the gallery is a challenging task, as a very low level of signal in comparison to environmental noise is expected in such environment. Monitoring required highly effective filtering of any possible noise resulting from processes other than fracturing in the wood structure. To prevent recording electrical and unwanted acoustic signals, the anti-correlation measuring scheme was utilised. Two identical AE sensors were connected to the opposite sides of the wardrobe, close to existing crack tips, at such a distance that events recorded by one sensor were out of the range of the other. By discarding events recorded by two sensors simultaneously, a serious reduction of the noise was achieved. A further reduction of the noise was possible by application of 60 kHz high-pass frequency filtering after the initial 45 days of the monitoring. It has been demonstrated [7] that signals with a high-frequency content are associated with fracturing of the wood structure whereas signals of low frequency are typical of ambient noise.
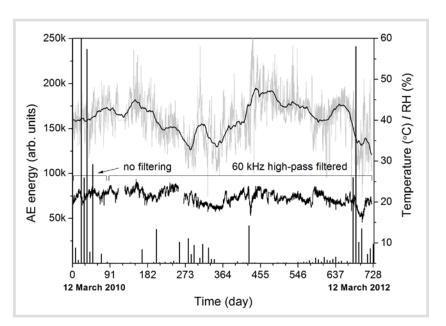
Parallel to the AE monitoring of the wardrobe, temperature and RH were measured every hour in the gallery with the help of the permanent museum system of microclimate monitoring. Comparison of the AE measurements with the microclimatic parameters in the gallery allowed the risk analysis for the monitored object to be performed, which is presented in the following sections.

Acoustic emission induced in the wardrobe by the climatic variations

The results of almost two years of monitoring the AE and climatic conditions in the gallery are presented in figure 5. As one can see, managing the indoor climate in the gallery was subordinated to the comfort of visitors and staff. Therefore, the temperature was maintained at approximately 20°C throughout the year with some periods of slight increases or decreases in summer and winter respectively. Though average RH was about 40 %, a distinct low-high seasonal cycle in RH was caused by heating in winter. According to the recent European standard (EN 15757, 2010) the

seasonal cycle was obtained by calculating, for each reading, the 30-day central moving average which is the arithmetic mean of all the RH readings taken in a 30 day period composed of 15 days before and 15 days after the time at which the average is computed. The seasonal RH cycle ranged from 47 % in May 2011 to 32 % in February 2012. The most pronounced falls in RH, recorded in December 2010, February 2011 and February 2012, were due to spells of particularly cold dry weather, when the outdoor air drawn into the museum was heated to the set temperature but was insufficiently humidified by the air-conditioning system.

A multi-step analysis of the data was performed focused on the risk of RH variations to the monitored object, as thermal expansion or contraction has a minor effect on the overall dimensional changes of the wood compared with its response to moisture. As the drops in RH during winter and the wood shrinkage they produce are the primary condition of concern, correlation was sought between the measured AE energy and the minimum values of RH recorded in the gallery during winter. It should be born in mind that the cracks in the wardrobe would propagate only when two conditions are simultaneously met. On the one hand, a fall in RH must go beyond a certain critical level, on the other, the variation must last longer than the response time of the wooden panels to bring about their dimensional change. The panels are approximately 10 mm thick. If one assumes that both panel faces have the same permeability to the diffusion of water vapour, the 95 % response time falls within the range of 5 to 7 days depending on the air velocity around the panel, i.e., if the adjacent air layer is calm or turbulent [4,10]. However, the response time of a panel can dramatically increase when wood is coated with any layers which hinder the moisture flow: the 95 % response times for a 10 mm panel coated with light, medium or heavy varnish are approximately 10, 20 and 40 days respectively [10]. An increase in the response time can be brought about also by the asymmetric diffusion through the uncoated back-face of the panel when the top face is coated with any kind of a finish layer blocking the moisture flow.

The detailed procedure of the analysis is illustrated in figure 6 for a time interval of one week corresponding to a response time of a

10 mm thick panel with two faces diffusively opened as discussed above. In the first step of the analysis, the weekly simple moving average for each RH reading is calculated, which is the arithmetic mean of all the RH readings taken in one week before the time at which the average is calculated. In this way, the short-term fluctuations are smoothed and the longer-term cycles to which the elements might have responded are emphasized. To each AE signal, represented by vertical bars in the figure, a corresponding value of the one-week RH average is attributed. The procedure is illustrated in figure 6 for three selected AE events.

In the next step of the analysis, the number of RH drops during the monitored period is established, as illustrated in figure 7, for the time period shown in figure 6. The smoothed one-week average RH plot is recalculated into a series of discrete decreases and increases of 1 % RH. The number of RH drops to each RH level can be then derived.

Finally, the energies of AE events corresponding to intervals with the same value of RH plus or minus 0.5 % RH were averaged, that is added and divided by the number of RH drops to that RH value. As the fracturing and the AE signals are caused just by RH drops, all AE events recorded were related in this way to a drop of at least 1 % in the one-week RH average. As 58000 arbitrary units (a.u.) was established in the calibration procedure as the energy released during the fracturing of 1 mm^2 of the wood area, or 0.1 mm of crack propagation for the 10 mm thick panel, the AE energy can be recalculated into the equivalent crack propagation. Figure 8 presents plots of the crack propagation averaged per RH drop to a given RH level. For comparison, the figure also shows plots obtained by the same data analysis but using time-intervals of two weeks and one month, corresponding to possible longer response times of the panels. The plots immediately reveal which response time is correct. As the process leading to damage is related to RH drops, the damage should be more and more severe with decreasing RH value. Such a tendency is observed most clearly for the one-week time interval, which indicates that the damage progress is due to RH variations of an approximate duration of one week or less.
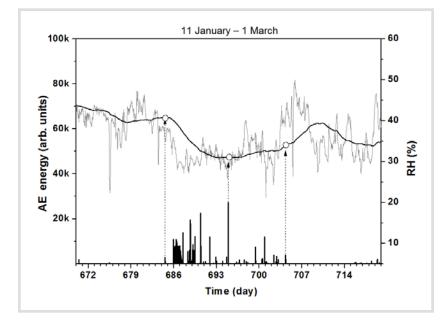
Figure 6. Indoor RH: original values recorded every hour (grey line), as well as simple moving averages calculated for a one-week time interval (black solid line). RH values related to three exemplary AE signals are marked

The total AE energy registered during the two-year monitoring period was 703000 a.u. Thus, the total area fractured was 12.1 mm^2 corresponding to 1.2 mm of crack propagation for the 10 mm thick panel, or 0.6 mm per year. The recorded crack propagation in the entire object is relatively small for any practical assessment of the damage. So the principal conclusion from the two-year monitoring carried out is that the climatic conditions in the gallery are relatively low risk for the collection.

However, amazing sensitivity and reproducibility of the AE sensors in detecting extremely small sources of acoustic signals has allowed further refining of the analysis. Figure 9 shows a plot of cumulative crack propagation which has occurred as a result of the RH drops in the entire two-year monitoring period. Calculations for the time intervals of one week, corresponding to realistic response times of the panels are provided.

The plots allow acceptable RH falls to be derived if a conservation professional or a curator were to agree a 'tolerable' magnitude of fracture, that is the magnitude below which an object's damage is considered insignificant. For example, an improvement in the present climate in the gallery by maintaining one-week average
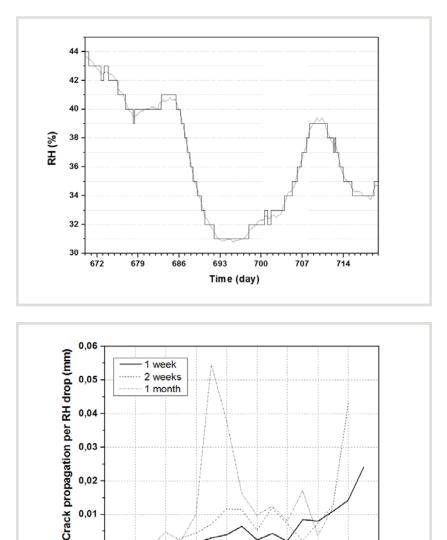
Figure 7. Indoor RH as simple moving averages for one-week time interval recalculated into discrete decreases and increases

Figure 8. Plots of average AE energy per RH drop to a given RH level
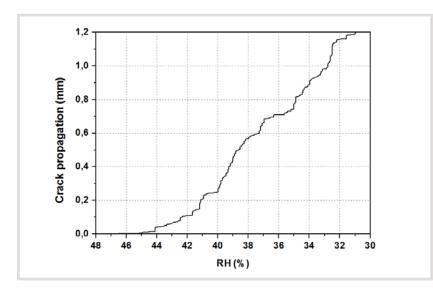
RH over 38 % at all times will halve the current yearly crack propagation in the wardrobe to 0.3 mm/year. If the allowable one-week RH level is further increased to 40 %, the yearly crack propagation will be reduced to mere 0.13 mm/year.

Conclusions: the re-evaluated indoor climate guidelines

Based on the outcome of these investigations, the National Museum in Krakow has embarked on reviewing its policy and practice regarding climate control so that the display conditions are better tailored to the clearly identified needs of the collections on one hand, and to the potential of a particular building for climate control on the other. The modified approach to climate control was first applied on the occasion of the comprehensive rebuilding, renovation and renewal of the historic seat of the Princes Czartoryski Museum in Krakow, which started in 2010.

The museum itself, the oldest in the country, has existed for more than 200 years. It has been housed in the current building in the historic centre of the city since 1901. The research and conservation team of MNK which advised on the preservation aspects of the renovation plan had the following challenge: ensure that this renowned museum meets current standards and preserve the historic architecture and exhibition design that has defined the museum. The climate-control guidelines devised require that during the summer temperature is kept between 22 and 25 °C and is lowered to between 18 and 22 °C in winter. As an emergency measure, the temperature can be further lowered on very cold days, when the indoor RH falls below 35 %, but never below 16 °C to ensure minimum comfort for visitors and staff. The RH is kept between 40 and 60 %, the efficient central humidifying and dehumidifying systems being responsible for the provision of the required conditions. The air entering the air-conditioning system is a mixture of outdoor air and re-cycled indoor air. Indoor carbon dioxide concentration is used to evaluate indoor air quality and building ventilation following the recommendation of the ASTM D 6245 - 07 standard [11]. The CO_2 sensors are installed in selected rooms of the museum. When the CO_2 level is above 1150 ppm, that is the level at which, according to the standard, approximately 20 % of visitors find the level of body odour unacceptable, outdoor air is supplied into the building, otherwise the indoor air is recycled.

With these guidelines, the size of the ducts through which the conditioned air will be supplied to the galleries could be considerable reduced. Consequently, lowering of the ceilings behind which the ducts are hidden was limited and the impact of installing the duct system on the original high ceilings in the rooms minimised.

References

[1] Bratasz, Ł., 'Allowable microclimatic variations for painted wood', Studies in Conservation (forthcoming).

[2] Ascione F., Bellia, L., Capozzoli, A., and Minichiello, F., 'Energy saving strategies in air-conditioning for museums', Applied Thermal Engineering 29 (2009) 676–686.

[3] Mecklenburg, M.F., Tumosa, C.S., and Erhardt, D., 'Structural response of painted wood surfaces to changes in ambient relative humidity', in Painted Wood: History and Conservation, ed. V. Dorge and F. C. Howlett, Los Angeles, The Getty Conservation Institute (1998) 464–483.

[4] Rachwał, B., Bratasz, Ł., Krzemień, L., Łukomski, M., and Kozłowski, R., 'Fatigue damage of the gesso layer in panel paintings subjected to changing climate conditions', Strain 48.6 (2012) 47–481.

[5] Rachwał, B., Bratasz, Ł., Łukomski, M., and Kozłowski, R., 'Response of wood supports in panel paintings subjected to changing climate conditions', Strain 48.5 (2012) 366–374.

[6] Michalski, S., 'The ideal climate, risk management, the ASHRAE chapter, proofed fluctuations, and towards a full risk analysis model', in Proceedings of Experts' Roundtable on Sustainable Climate Management Strategies, Tenerife, 2007, ed. F. Boersma, Los Angeles, Getty Conservation Institute. Available at: http://www.getty.edu/conservation/our_projects/science/climate/paper_michalski.pdf (accessed 19 April 2013)

[7] Jakieła, S., Bratasz, Ł., and Kozłowski, R., 'Acoustic emission for tracing the evolution of damage in wooden objects', Studies in Conservation 52 (2007) 101–109.

[8] Künzel, H., Simultaneous Heat and Moisture Transport in Building Components. One- and Two-dimensional Calculation using Simple Parameters, IRB Verlag, Fraunhofer-Informationszentrum Raum und Bau, Stuttgart (1995).

[9] Strojecki, M., Łukomski, M., Sobczyk, J., Krzemień, and L., Bratasz, Ł., Studies in Conservation (submitted for publication).

[10] ASHRAE, 'ANSI and ASHRAE Standard 62.1. 2007', in Ventilation for Acceptable Indoor Air Quality, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA (2007).

[11] ASTM, D 6245–07. Standard guide for using indoor carbon dioxide concentrations to evaluate indoor air quality and ventilation (2007).

Authors

Michał Łukomski is a member of staff of the Institute of Catalysis and Surface Chemistry, Polish Academy of Sciences, Krakow. Email: nclukoms@cyf-kr.edu.pl

Janusz Czop is the Chief Conservator of the National Museum in Krakow. Email: jczop@muzeum.krakow.pl

Łukasz Bratasz is head of the research laboratory in the National Museum in Krakow and research fellow at the Jerzy Haber Institute of Catalysis and Surface Chemistry Polish Academy of Sciences. His research focuses on the response of materials to changes in environmental parameters, development of non-invasive measures of damage tracing as well as implementing measures to prevent damage to the collections. Email: ncbratas@cyf-kr.edu.pl

Marcin Strojecki is a research fellow at the Institute of Catalysis and Surface Chemistry, Polish Academy of Sciences, Krakow. Email: ncstroje@cyf-kr.edu.pl

How the usual museum climate recommendations endanger our cultural heritage

Andreas Schulze

Abstract

Recommended environmental conditions for collections became common in the international museum world from the middle of the last century. These targets mainly defined ranges of relative humidity at certain room temperatures and also set the limits of any acceptable fluctuations from these parameters for different materials and different groups of items. Today, these demands for 18 to 22 °C and x % relative humidity all year round are accepted as canonical not only by museum professionals but also by those who care for other types of cultural heritage like churches or historic houses. In practice, these recommendations can only be met with the use of extensive technical equipment or in buildings specially constructed to meet these specifications.

However, when visiting our historic monuments, for example castles, manor houses or churches, it is striking that innumerable pieces of art and culture have survived in an excellent state of preservation under environmental conditions which are far from the recommended museum climate. In central Europe, the average values of the original climatic conditions in historic buildings are normally colder and more humid than in the theory of 'harmless museum environments' and follow the seasonal cycle of the climate outside the buildings.

This paper will describe the personal experiences of the author concerning these problems through selected examples. It will be focused on historic buildings with complex interiors and on the differences between the 'original' environmental conditions of the buildings and the so-called 'museum climate'. It will also consider the problems air-conditioning or heating systems can cause for the buildings and for parts of the original interiors associated with the exterior walls. In the second part, the paper will discuss the actual recommendations for 'museum climates', particularly those for temperature. Finally, it will illustrate some proposals for alternative strategies with examples of interventions on monuments in Saxony.

Introduction

In the course of the last 100 years, the intensive examination and discussion of the mechanisms of the action of harmful environmental influences on our cultural heritage has resulted in the development of climatic standards for the preservation and presentation of historic objects. The perception of serious, in most cases physical and clearly visible, damage on historic artefacts as the result of unsuitable environmental conditions was the starting-point for efforts to establish these 'standards'. The original goal was to create climatic environments which would be 'completely safe' for museum collections and which would allow a free transfer of objects for exhibition purposes worldwide. Today

these standards contribute to the basic professional knowledge of conservators, curators, exhibition managers and engineers within and beyond the museum world. If one were to consult either the extremely comprehensive literature on this topic or colleagues in a museum about the desired values of temperature and relative humidity for wooden artefacts, in most cases the following would be specified: 21 °C and 55 % relative air humidity (RH) with only slight fluctuation above and below these fixed values. For some groups of materials, for instance paper, we will find deviating recommendations in respect of relative humidity, but the values of the recommended temperatures are more or less the same and in the range of 'room temperature', which means in the range of human comfort. Climatic conditions within these limits are usually considered 'harmless' and 'safe' for historic objects, conditions outside these 'standards' as 'dangerous'. And very often these estimations are done on the basis of the measured conditions in the indoor air without regard to the real situation experienced by the object. Is this really correct from a scientific perspective?

These recommendations for the 'museum climate' have become so firmly codified in our professional world that more recent scientific research, for instance into the influence of temperature on the speed of degradation processes in organic materials, has been ignored in most cases and has not lead to any general revision of the climatic standards for museums [1, 2]. Only in the case of paper-based objects or of photographic materials have new recommendations been introduced to some libraries and archives, which consider these insights.

In over 23 years as a professional conservator-restorer for the preservation of cultural heritage I have worked with countless historic objects, among others paintings, polychromed sculptures and complex historic interiors, which had survived over centuries in an excellent state of preservation under apparently 'completely

Table 1. Influences of RH and temperature on the equilibrium moisture content in pine wood [3]

RH [%]	equilibrium moisture content [weight %]						
temperature [°C]	10 °C	15 °C	20 °C	25 °C	30 °C	35 °C	40 °C
90	21.1	21.0	21.0	20.8	20	19.8	19.3
85	18.1	18.0	18	17.9	17.5	17.1	16.9
80	16.2	16.0	16	15.8	15.5	15.1	14.9
75	14.7	14.5	14.3	14.0	13.9	13.5	13.2
70	13.2	13.1	13.0	12.8	12.4	12.1	11.8
65	12.0	12.0	11.8	11.5	11.2	11.0	10.7
60	11.0	10.9	10.8	10.5	10.3	10.0	9.7
55	10.1	10.0	9.9	9.7	9.4	9.1	8.8
50	9.4	9.2	9.0	8.9	8.6	8.4	8.0
45	8.6	8.4	8.3	8.1	7.9	7.5	7.1
40	7.8	7.7	7.5	7.3	7.0	6.6	6.3
35	7.0	6.9	6.7	6.4	6.2	5.8	5.5
30	6.2	6.1	5.9	5.6	5.3	5.0	4.7
25	5.4	5.3	5.0	4.8	4.5	4.2	3.8

Table 2. Annual averages of the climatic outdoor conditions of three places in Saxony, which are located in different areas about 20 km from each other, with the resulting equilibrium moisture content of air-seasoned pine wood [4]

location and height above sea level	annual averages of the outdoor conditions			
	temperature [°C]	relative humidity [%]	absolute humidity [g/m³]	resulting equilibrium moisture content of pine wood, air dried [%]
Dresden (120 m)	9.1	76	6.64	14.8
Dippoldiswalde 356 m)	7.7	82	6.61	17.0
Zinnwald (877 m)	4.1	86	5.48	18.7

dangerous' climatic conditions, or where existing damage had been caused by other reasons. On the other hand, I have seen many objects which were seriously damaged despite strict obedience to the 'museum climate standards'. It should logically be the case that no change in environmental conditions is necessary in a historic building, for example a castle or church, if the historic substance shows no damage caused by a poor environment. Unfortunately, this is not always the common practice!

A particularly impressive example is the hunting castle Moritzburg near Dresden, which houses many historic interiors and the world's largest collection of baroque gilt leather wall hangings. The exhibition rooms of this castle are traditionally unheated; the values of temperature and RH inside the rooms follow the outdoor climate during the course of the year though significantly attenuated. The room climate fluctuates over the year between 3 and 26 °C with an RH of between 45 and 85 %, with annual averages of 11 °C and 65 % RH. Depending on the position of the rooms in the castle these values differ a little from each other. But the precious interiors with many types of artefacts and groups of materials present minimal or no damage that can be considered the result of harmful climatic influences. There are no signs of mould inside the castle, which is explained by the fact that the high values of relative air humidity are present only in winter in combination with low temperatures. However, about ten years ago we had a long and intensive controversy about the climatic conditions in this castle.

The starting point of this controversy was the statement by an engineering company for climate control and heating systems and by the state's building administration that the climatic conditions in Moritzburg castle were 'irresponsibly cold and humid' and that it would be absolutely necessary to change this 'terrible situation' with a technical solution concerning the 'museums climate recommendations' without delay. It was proposed to reach this goal with the installation of so-called 'conservation-friendly heating' and to lower the RH to 50 to 55 % by increasing the room temperature at all times of the year in those rooms with higher values of humidity, if necessary in the summer too (!). Self-evidently, the true motives for that proposal were not concerns about the historic objects and interiors, but to sell products and to achieve environmental conditions which would extend the possibilities of using the castle more intensively. It took us three years of discussions and 'fights' to repel this project. Moritzburg castle will stay unheated in the future.

Discussion of the traditional museum climate recommendations

What are the implications of installing heating or air-conditioning systems in a historic building in order to protect and to preserve its original state? The necessary cabling for hot-water heating or for ventilation ducts interfere profoundly with the building's structure, particularly if the intention is that the visitor should not see these technical installations. Often enormous financial and technical efforts are required, not only in terms of investments costs, but also in connection with ongoing running expenses. The systems themselves also pose potential risks of damage in the event of leakage or malfunction. In many cases the high expenditure of energy triggers follow-up actions to increase energy efficiency, for instance installing new windows or, in the worst-case scenario, with thermal insulation of the entire building. Ultimately, there may not be much historic fabric left worth conserving and it is also debatable whether the conditions for the cultural treasures inside the building are really improved! Each intervention into the existing 'system' of the construction physics of a historic building and its interior has numerous consequences for each element of this overall system. Where the existing indoor climate of a historic

Table 3. Annual averages of the climatic conditions inside selected unheated and unconditioned historic buildings in Saxony, with the resulting equilibrium moisture content and tangential shrinkage of pine wood which would result if the objects were transferred to a 'museum climate' [5]

Nr	location and name of the building and its height above sea level	annual averages of the indoor conditions				calculated tangential shrinkage of pine wood in %, if transferred from these locations into the 'museum climate' (0.32 % per 1 % EMC)
		temperature [°C]	relative humidity [%]	absolute humidity [g/m³]	resulting equilibrium moisture content of pine wood [%]	
	'museum climate'	21	55	10.12	9.9	–
1	Pillnitz, Neues Palais (115 m)	14.93	60.18	7.81	10.9	0.32
2	Radebeul, castle Hoflößnitz (140 m)	15.18	58.33	7.81	10.8	0.29
3	Moritzburg, hunting castle (173 m)	11	65	6.46	12.0	0.67
4	Kamenz, monastery church St. Annen (195 m)	10.95	75.31	7.82	14.7	1.54
5	Bautzen, cathedral (222 m)	11.32	71.48	7.32	13.4	1.12
6	Wolkenburg, castle (246 m)	14.89	59.69	7.63	10.9	0.32
7	Wildenfels, castle (351 m)	13.87	58.08	7.16	10.8	0.29
8	Augustusburg, castle (515 m)	13.66	69.62	8.37	13.1	1.02
9	Lauterbach, fortified church (598 m)	8.03	80.57	6.86	16.2	2.02
10	Schönberg (Vogtland), castle (600 m)	11.04	68.31	7.02	12.9	0.96

Table 4. Differential degree of radial and tangential shrinkage of different types of wood in % per % equilibrium moisture content [6].

type of wood	differential degree of shrinkage in % per % equilibrium moisture content	
	radial	tangential
coniferus wood		
spruce	0,19	0,39
pine	0,19	0,36
larch	0,14	0.30
fir	0,14	0,28
ceciduous wood		
beech	0.20	0,41
oak	0,16	0,36
ash	0,21	0,38
walnut	0,18	0,29
poplar	0,13	0,31
lime	0,19	0,29

building has been changed with heating or air conditioning, the final result shows different annual environmental averages, with higher room temperatures and lower relative humidity.

It is generally known that the moisture content of organic, but also of many inorganic, porous materials will reach equilibrium with the values of RH and temperature in the immediate environment. Alterations of an object's moisture content result in dimensional changes, particularly in the case of organic materials, which can induce further diverse processes of damage. The real consequences of climatic alterations to the moisture content of objects are dependent on many factors or influences, such as the material's dimensions, the presence of surface coatings, the position of the object in the overall context of the room and respectively of the building, exposure to air flow or the presence of moisture-buffering materials in the environment. However, not only the range of the climatic fluctuations but also the long-term average of the climate values are relevant for the material's moisture content. This is why each modification of the annual average of temperature and air moisture will provoke reactions in the objects, no matter how slowly the process of change is introduced. The next factor to be addressed is, in my opinion, very important in the discussion of climatic recommendations: the 'historic' or 'object-specific' climate. I want to illustrate this with the example of wood, which was used across all epochs and regions for the making of pieces of art and culture and for buildings too. It can be assumed that in most cases, at least in well-forested regions, wood from the immediate surroundings was used for buildings and furnishings, which would have been seasoned in the air until well into the age of industrialisation. The natural air-drying of wood is a very slow process and is a function of its dimension; many historic guild laws took this into consideration in their specific regulations. During these painstaking drying procedures, the moisture content of the wood can never become lower than its state of equilibrium with the temperature and moisture content of the surrounding atmosphere!

Figure 1. Clearly visible example of shrinking reactions of a baroque door inside Moritzburg castle, after the room was equipped with air conditioning to be used as a conservation workshop. Doors of the same type in the unheated exhibition rooms of the castle do not present these cracks around the door fillings.

If air-dried wood was used for the making of buildings or objects of art, all the dimensions of the wooden parts would correspond with its initial moisture content. The interiors of historic buildings, for example, castles or churches would not originally have been heated, or perhaps only heated slightly, so this 'original' moisture content of the wood would not have changed significantly while the objects and interiors were in use but rather the values would have remained in a natural state of equilibrium with the indoor climate, which was would have followed very closely the local outdoor climate. If the climatic average of a building is known, it is not difficult to calculate the average moisture content of the wood quite precisely. In this context it is very interesting to see how considerable the impact of temperature is on the state of equilibrium of the wood moisture content (Table1).

It is a well-known fact that outdoor microclimates can develop with marked differences between places which are geographically very close, due to factors such as the height of the sites above sea-level. This fact has implications for indoor climates. Some examples are presented in table 2.

Many measurements of the moisture content of wooden objects in historic buildings attest that the calculated and the real measured values correlate very well. If there are no other sources of humidity, the moisture content of the wood is in a very stable balance with the indoor climate. It is possible to calculate the 'object-specific' wood moisture content and to forecast its changes in the case of any alteration from the traditional climatic conditions inside a building (Table 3).

If the average indoor climate of Moritzburg castle, for example, which is currently 11 °C and 65 % RH were adapted to the 'ideal museum climate' of 21°C and 55 % RH, the moisture content of a door or a panel of spruce wood would drop by approximately 2 %, from 12 % to 10 %. The connected dimensional change of the wood (Table 4) is not simply academic, it would be visible in reality too (Figure 1).

The same patterns of deterioration would be observed if a wooden altarpiece with polychromed sculptures and panel paintings

(Figure 2) or a piece of furniture were to be transferred from an unheated church to an exhibition gallery with a 'museum climate'. The change in dimensions would be particularly detrimental because the shrinking of the wood provokes cracks and the loss of paint layers (Figures 3–8).

So it is possible and necessary to state the following:

- The traditional climate conditions in historic buildings differ fundamentally from the so-called 'museum climate'.
- In central Europe the 'original indoor climate' is colder and more humid than the existing recommendations for the preservation and presentation of objects of art and culture. In other regions the trend of these divergences may be different.
- Depending on the very different local climatic conditions the respective indoor climate of the buildings can differ too and should always be considered from an 'object-specific' perspective.
- Many objects have survived over centuries in a very good state of preservation under climatic conditions which are contrary to the existing 'rules for museums'.
- A material's moisture content will not only have become acclimatised to 'historic' climate conditions, many (or most) historic objects will also have been created under and specifically for such conditions. Very often the artistic and technological details of an artefact will have been optimised for the climatic conditions that existed when it was originally produced.

Figure 2
Polychromed wooden retable from the late gothic period.

• Technical interventions in the indoor climates of historic buildings with the aim of achieving the usual standards for museum climates will induce significant changes of the equilibrium moisture content, which will cause serious dimensional change.

One of the frequent arguments concerning the 'harmful original climate' and the 'safe museum climate' is the assertion that values of RH higher than 60 % would be connected inevitably with the growth of mould on the objects. During my professional life I have seen many historic buildings with cold and humid indoor climate conditions without any signs of mould. If the 'original climate' dominating in these buildings over centuries had provoked the growth of mould more or less automatically, most objects would have not survived until today! Nevertheless, mould is also found sometimes in historic buildings which have never previously presented such problems. In these cases it is very important to search carefully for the real causes of the mould infestation. In reality there are many factors besides the relative air humidity which influence the development of mould, for instance the type of substrate ('food availability'), the temperature, the air circulation rate and other sources of humidity, but also the pH-value or the water vapour permeability of the surface [7]. Generally we can presume that the risk of mould is low when high RH-values are combined with low temperatures as in unheated historic buildings during the cold season [8].

There are much higher risks of mould in traditional buildings where the indoor climate is conditioned according to the usual 'museum climate recommendations', and where the water vapour becomes condensed on the walls and on other cold surfaces during the winter. If an exhaustive search is carried out into the causes of mould in historic buildings maintained with their 'original climatic conditions', in many cases there will be other reasons identified rather than simply high RH levels: for instance, the installation of tight-closing windows with reduced air exchange, or the use of synthetic paints or consolidants, which lower the water vapour permeability or the pH-value of the surfaces. For example, mould was identified on the wall surfaces in a room of the 'Fasanenschlösschen' near Moritzburg, which had been renovated years ago with 'modern' dispersion paints. Under exactly the same climatic conditions, there is no mould on the walls painted in the

Figures 3–6.
The retable in figure 2 shows signs of serious dimensional loss in all structural parts, which indicates the lowering of the wood moisture content because of changed climatic conditions

Figures 7 and 8.
Typical damage to polychrome carvings (finial of a Rococo confessional box), caused by shrinking reactions of the lime wood after shipping the object from its original place in an unheated church to a conservation atelier, which was conditioned to the 'standard museum climate' of 55 % RH and 21 °C

traditional way with paints bound with protein (!) glue. After the removal of these dispersion paint layers in the infested room, the problem of the mould was remediated without changing anything in respect of the climatic conditions.

Another essential factor from a conservation perspective is the indoor temperature in museums, which is usually set in the range of human comfort. This practice neglects the recent insights into the significant influence of temperature on the speed of degradation processes in organic materials, as pointed out initially by Stefan Michalski in 2002 [1]. During my investigations into the gilt leather hangings of Moritzburg castle, it was possible to attest to these insights [9]. The 'remaining lifetime' of the hangings would be shortened by 75 % if the yearly average of temperature in the castle were increased from its current 11 °C to the 21 °C of the usual 'museum climate'. In my opinion, the recommended indoor temperature for museums is a very weak concession to the comfort of visitors and staff, not a scientifically proven conservation argument. If we want to take into account the necessity of sustainability and energy saving we have to reduce the energy input into buildings generally. We also have to question whether it would be better to use historic buildings in ways which are more suited to their existing conditions rather than to adapt a historic building to the exaggerated interests of other beneficiaries. The interests of the preservation of cultural heritage are becoming unified with the requirements of environmental protection, and the principles of sustainable tourism become more and more relevant.

What are the consequences of these observations?

- The existing recommendations for museum climates are not applicable to historic buildings and their furnishings and can cause damage in these objects.
- Even for museum collections these recommendations are only a poor compromise of opposed interests, which disadvantage the objects.
- There are no general climatic target ranges which would be really safe for all items within a certain group of objects or materials.
- It is necessary to understand the specific climatic conditions under which an artefact was made and under which it has stood the test of time.
- More care has to be taken about the moisture content and temperature of the materials which make up objects rather than considering only the RH and temperature of the ambient air.

- Changes of the ambient climatic conditions should be considered only in cases where existing conditions have caused verifiable damage to objects. All other possible causes of damage should be ruled out before technical interventions are made.
- Any intervention should be made with substance- and resource-saving technologies or with 'passive' methods. It would be better to reduce high peaks of air humidity with controlled ventilation rather than by installing a heating system. The targeted use of the climate buffering effect of historic construction methods and materials should be considered.
- Finally, the real needs of the objects should be the decisive factor for the intensity of their use.

Examples for alternative strategies

These principles have been applied very successfully in many historic buildings and interiors all over Saxony. Besides the baroque hunting castle in Moritzburg, other examples are the altarpiece by Lucas Cranach the Younger in the chapel of Augustusburg castle [10], the fortified church in Lauterbach near Marienberg, the so-called 'Fasanenschlösschen' near Moritzburg with many precious interiors or the 'Blaue Salon' in Wildenfels castle with a unique wall covering of Ottoman embroidery [11] and many others. Automatically controlled ventilation was used to stabilise the indoor climate of the chapel in Augustusburg and the church in Lauterbach. In the case of the Cranach-altarpiece it was also possible to stabilise the huge and very sensitive panel painting with a wooden construction mounted on the back of the panel, which buffers the alterations of RH very efficiently. The buffering effect of wooden panels was also used for the construction of a new mounting system for the gilt leather wall hangings in the 'Damenbildniszimmer' in Moritzburg castle, with the goal of minimising the dimensional reactions of the leather to climatic changes [12]. In the 'Fasanenschlösschen', the eighteenth-century building climate was re-established and the intensity of its use as a museum was limited in response to these specific conditions. The castle is open to visitors from the beginning of May until the end of October, but closed during the cold season. Additionally, the number of visitors is limited to 10 people per group and two groups per hour. The recreation of the original climate has proved successful for the preservation of the very complex interiors and their many delicate materials. The same success has been achieved in the 'Blauen Salon' at Wildenfels, where the existing heating system and the double-glazed windows of the 1960s have been removed in order to reinstate the original environment. Of course, these interventions were proposed on the basis of extensive monitoring programmes and their success has been demonstrated by similarly comprehensive monitoring.

Conclusion

Replacing the traditional climatic standards for museums with object-specific requirements and specifications makes the work of the conservator-restorers and all other partners involved in the preservation of cultural heritages more difficult. The determination of the correct environmental conditions for conservation must be based on sound scientific principles and this increases the professional burden of our responsibility. However, there are no alternatives if we want to take the objectives and the ethical standards of our profession seriously.

References

[1] Michalski, S., 'Double the life for each five-degree drop, more than double the life for each halving of relative humidity', in Preprints of the 13th ICOM-CC Triennial Meeting in Rio de Janeiro (22–27 September 2002), ed. R. Vontobel, James & James, London (2002) Vol. I 66–72.

[2] Luxford, N., Thickett, D., and Wyeth, P., 'Applying preventive conservation recommendations for silk in historic houses', in Proceedings of the Joint Interim meeting Rome 2010, Multidisciplinary Conservation: a holistic view for historic interiors, ed. E. Janssen, ICOM-CC, Rome (2010), http://www.icom-cc.org/54/document/applying-preventive-conservation-recommendations-for-silk-in-historic-houses/?id=813#.UDJUaYGxg2p.

[3] Source: http://www.holzfragen.de/seiten/ausgleichsfeuchte.html - there cited after R. Keylwert and data of the U.S. Forest Products Laboratory, Madison (1951).

[4] Source of the outdoor-climate data: Amt für Meteorologie Dresden (1951–1980).

[5] Source of the indoor-climate data: Thomas Löther, Institut für Diagnostik und Konservierung an Baudenkmalen in Sachsen und Sachsen-Anhalt e.V. (IDK).

[6] Source: http://www.holzhandel.de/qls_differentielles_schwindmass.html.

[7] IHD Institut für Holztechnologie Dresden gGmbH, 'Abschlussbericht zur Entwicklung verbesserter Restaurierungsprodukte und -maßnahmen zur Sanierung und Vorbeugung von Schimmelpilzbefall in Kirchen und an sakralem Kunstgut', Projektförderung durch das Bundesministerium für Wirtschaft und Arbeit, Projektträger EuroNorm GmbH Berlin, Projektzeitraum 11/2003 bis 10/2005.

[8] Sedlbauer, K., Schimmelpilze innen, Algen außen – gibt es eine Lösung?, Frauenhofer-Institut für Bauphysik Holzkirchen, see esp. fig. 5, 9, http://www.ibp.fraunhofer.de/content/dam/ibp/de/documents/KB_3_tcm45-30958.pdf.

[9] Schulze, A., Goldleder zwischen 1500 und 1800 – Herstellung und Erhaltung, Arbeitsheft 17 des Landesamtes für Denkmalpflege Sachsen, Dresden (2011) 117.

[10] Eisbein, M., Kempe, O., Löther, T., and Weiß, B., 'Die Bildträgerkonservierung und statische Sicherung des Augustusburger Cranach-Altars', in Beiträge zur Erhaltung von Kunst- und Kulturgut, ed. Verband der Restauratoren VDR, Heft 2 (2009) 24–46.

[11] Naumann, R., Schulze, A., and Löther, T., 'Der Blaue Salon auf Schloss Wildenfels - Ein einzigartiges Interieur mit osmanischen Seidentapeten', in Mitteilungen des Landesamtes für Denkmalpflege Sachsen, Jahrbuch 2012 [forthcoming].

[12] Schulze, A., 'First experiences with a light metal stretching frame-system for leather tapestries in climatically instable rooms', in ICOM Committee for Conservation, ICOM-CC, Working Group no. 10 - Conservation of leathercraft and related objects: interim meeting on the treatment of and research into leather, in particular of ethnographic objects: at the Central Research Laboratory for Objects of Art and Science, Amsterdam, 5-8 April, 1995, ICOM Committee for Conservation, Working Group no. 1, Amsterdam (1995) 26–33.

Author

Andreas Schulze is Professor for Art Technology and Conservation-Restoration of Sculptures and Interior decorations at the Academy of Fine Arts in Dresden. Email: aschulze@hfbk-dresden.de

Licence

Field-tested methodology for optimizing climate management

Jeremy Linden, James M. Reilly and Peter Herzog

Abstract

The Image Permanence Institute (IPI) has had an active research program concerning sustainable climate management in museums, libraries and archives for more than 15 years. During this time IPI has done materials response research in the laboratory, applied field research in numerous institutions, and undertaken efforts to create climate assessment algorithms, software and hardware. This paper describes a methodology for attaining optimal climate management in existing institutional circumstances. Optimal climate management is defined as the best balance between collections preservation, sustainable practices and energy costs. Elements of this methodology can also be useful in design and specification of new buildings.

The current debate over proper standards and guidelines for environmental conditions, though driven in part by increased knowledge of object behavior, is also propelled by the need to reduce operating costs and output of greenhouse gases. Optimal climate management is a complex matrix of decisions influenced not only by standards and guidelines, but by a host of locally specific circumstances including the needs of the collection, local weather conditions, building construction and architectural significance, mechanical systems (or lack of them), staff knowledge and attention and many other factors. It is a group activity that, to succeed, must involve various specialists (principally those representing the collections' well being, the operations and costs of building maintenance climate creation, the comfort of staff and visitors and those concerned with sustainability). The decisions and actions from such a climate management team are best taken when the group has a quantitative basis for:

1. The facts of the prevailing environmental conditions and their meaning for the health of collections, and
2. The amount and costs of energy consumed to create such conditions.

Introduction

For the past several decades, advancement in the creation and management of preservation environments has largely revolved around the improvement or control of temperature and relative humidity (RH) conditions according to prevailing standards and guidelines. Ranging from flat-line control with ultra-modern mechanical systems to simply managing the extremes of temperature and RH with little to no mechanical intervention, these practices have evolved with preservation as their core concern. Energy consumption resulting from those practices was either defended and justified by the preservation need or, in some cases, simply not considered. Today, institutions are faced with

declining budgets and increasing energy costs that, in combination with the public and professional demands of sustainability and environmental responsibility, often lead to institutional mandates regarding energy efficiency and reduction of carbon footprint. The former practice of unexamined energy usage in the name of collections preservation is no longer viable, but neither are energy savings sufficiently desirable to justify allowing cultural heritage to suffer unwarranted damage. The challenge is to find the optimal blend of energy consumption without sacrificing the quality of the preservation environment.

Viewed in these terms, the creation of the optimal preservation environment, which is the environment that achieves the best possible preservation of collections, with the least possible consumption of energy, and is sustainable over time, becomes an objective goal for new strategies. Collections preservation no longer stands as an independent goal; it both influences and is influenced by numerous surrounding factors that must be taken into account. The goal is now a holistic understanding of the needs and characteristics of the collection, the mechanical system that creates the environment (if applicable), the building, the outdoor climate, and the infrastructure and capabilities of the institution and its staff, among other factors. The incorporation of this mentality into institutional practice and workflow has the potential not only to save energy, but also to improve the preservation environment, as key inefficiencies and self-imposed limitations, often based on outdated practices, are discovered. To this end, the Image Permanence Institute (IPI) has developed a practical methodology through our fieldwork that can be outlined in five steps, and that covers the necessary procedures, staff, and resources necessary to document and analyze the environment and the energy used to create it, with optimization as the end goal. This is a process, not a one-time project, which provides cultural institutions with the best opportunity to turn the apparently competing demands of preservation environments and energy savings into a forward-thinking strategy for sustainable preservation environments.

Changing preservation environment standards

Achieving the 'best possible preservation' of collections presents the immediate challenge of defining the best possible preservation environment when, by nature, those very environments are a unique set of circumstances based on individual collections, mechanical systems, buildings, policies and outdoor climates, just to name a few factors. For years, a default recommendation of 21 °C and 50 % RH with minimal fluctuation was entrenched in both our minds and in the literature; the past 15 years have been spent in slow, though now rapidly accelerating, adjustment. Thanks to Donald Sebera's research on isoperms [1] and IPI's application of that knowledge to develop the Preservation Index and Time-Weighted Preservation Index Preservation Metrics™ [2], we recognize that cooler temperatures and lower RH slow the rate of chemical decay of organic materials and that the rates of such decay are quantifiable. Research by Marion Mecklenburg and David Erhardt has shown that maintaining tight RH control is often unnecessary due to many materials' ability to experience elastic shape-change in RHs fluctuating between roughly 30 to 60 % without suffering any permanent damage [3]. The traditional 21 °C and 50 % RH guideline, far from a universally ideal environment,

is giving way to our understanding that cooler temperatures and moderate RHs, when possible, are better for our collections.

This understanding also allows us to take the initial steps toward the 'least possible consumption of energy' portion of the optimal environment. Flat-line control of indoor environments, if held in opposition to the outdoor climate, creates a significant energy demand. Many climates have seasonal periods where cooler conditions and moderate RHs are far more economical and sustainable to produce. Current research into the equilibration rates of materials shows that while temperature equilibration at an object's core often occurs within a matter of hours, moisture equilibration at the core can take weeks or longer [4]. Improved understanding of moisture equilibration allows the potential for more creativity in designing sustainable solutions for preservation environments. A deliberate, risk-managed approach, as outlined in this paper, can benefit both collections preservation and energy usage.

Methodology
Step one: documentation

The process begins with identifying and gathering the resources and information available to the institution about the collections environment and the building. Our experience has taught us that an institutional champion, often from the collections staff, should shepherd the process and convene a process team from among collections, facilities, and administrative staff. This cross-disciplinary approach (Figure 1) brings together both the expertise and the resources of the major stakeholders in the process, and allows for direct addition of relevant knowledge into a single, shared repository of information.

The goal in documentation is two-fold: to gather information regarding the collections environment, systems, building and energy use, and to raise the shared level of knowledge among all the participants. Guided walkthroughs of collections spaces and mechanical rooms increase staff familiarity with spaces they may not have previous experience with; that familiarity improves communication and clarity as the team moves forward. Using a building floor plan as a starting document, the collections staff can annotate the location, type, significance and environmental needs or vulnerabilities of collections. A portion of the building and mechanical system documentation can be provided by facilities staff, especially as it relates to the system and structure's interaction with the outdoor climate. Tracing the location of any mechanical systems, the physical areas or zones that they serve, and noting the environment that they are designed or set to create provides a base set of information on the creation of the environment. Details of the building and roof, amounts of insulation or vapor barrier or types of windows help define what the mechanical systems can achieve when confronted with the outdoor climatic conditions. In the case of historic or architecturally significant structures that are themselves part of the collection, collections and administrative staff will be able to provide guidelines regarding what changes, interior or exterior, may be explored without harming the building's cultural integrity.

Thoroughness in documentation is key; a missed detail, for example, the temperature of available chilled water, or the

presence of sensitive acetate film in a storage area, can not only cost the process team valuable time in discussion and deliberation, but, if not caught, can increase the risk posed to the collections by proposed solutions. Where available, information from preservation surveys, collections policies and condition assessments should be included in the team's repository. Where mechanical systems are present, an understanding of their components and capabilities, the exact zones they serve, and the environment they currently create is critical. Design drawings provide an excellent start, but often do not document changes made over time and current operation. The aim should be to document, either on the drawings or by cartooning or freehand sketching (Figure 2), the current system components, their layout, and the spaces that they serve.
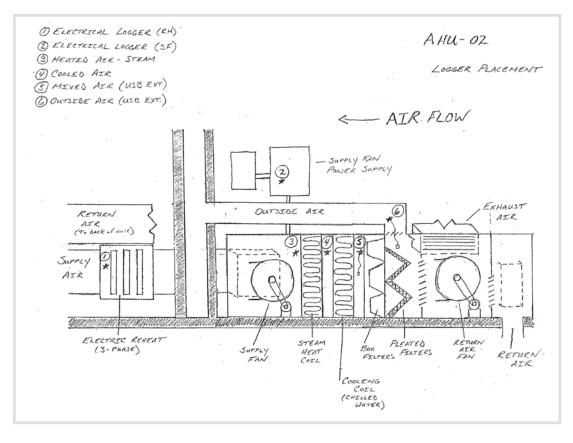
The final aspect of documentation is recording the current state of energy usage and sustainability practices and improvements in the institution, and stating any specific goals, mandates, or guidelines that may exist. Administrative staff can provide the past several years of utility bills for the institution, which should be analyzed for changing trends, such as increases in commodity costs, or changes in billing, such as the introduction of a peak demand charge in electric usage. Changes to practice or infrastructure, such as adjustments to lighting schedules or a switch to light-emitting diodes, installation of more efficient equipment or insulation, should be noted and their impact, if quantified, should be taken into account. Any existing institutional goals or mandates, whether specific, such as a 30 % reduction in carbon footprint in five years, or broad, such as a commitment to sustainable practices, should be documented. These frame the process, defining a minimum institutional goal that the team is looking to support, and provide a benchmark that the team's efforts and accomplishments can be measured against.

As mentioned above, the underlying goal in the extensive documentation process is to use the data gathered to determine the level of risk posed to collections or to the building through changes to indoor environments and patterns of systems operation. Risk factors such as particularly sensitive collections, extreme outdoor climates, poorly maintained or unreliable systems and problematic building envelopes can all increase the likelihood that changes in operation may cause more harm than benefit. Though not all potential risks can be mitigated, awareness allows the process team to account for them in the experimentation and implementation phase.

Figure 1.
Communication among the process team, which should include relevant parties from the collections, facilities and administrative staff, and may include contractors or consultants, is crucial when working toward an optimal preservation environment

① ELECTRICAL LOGGER (RH)
② ELECTRICAL LOGGER (SF)
③ HEATED AIR - STEAM
④ COOLED AIR
⑤ MIXED AIR (USB EXT.)
⑥ OUTSIDE AIR (USB EXT.)

AHU-02

LOGGER PLACEMENT

← AIR FLOW

SUPPLY FAN POWER SUPPLY

EXHAUST AIR

OUTSIDE AIR

RETURN AIR (To back of unit)

SUPPLY AIR

ELECTRIC REHEAT (3-PHASE)

SUPPLY FAN

STEAM HEAT COIL

COOLING COIL (CHILLED WATER)

BOX FILTERS

PLEATED FILTERS

RETURN AIR FAN

RETURN AIR

Figure 2. A sketched cartoon of a mechanical system can quickly communicate to the entire process team both the components contained within the mechanical system as well as their location. Noting the locations of dataloggers within the system helps the data retrieval process and creates a shared knowledge of what the data is and where it came from

Step two: data gathering

The second step is to ensure that sufficient temperature and RH data exist to evaluate the conditions experienced by the collections and created by the mechanical systems; it consists of two parts: the gathering of the raw data from the collections environment and the analysis of that data. While there are several methods and sources for gathering raw data, IPI's practice has shown that the use of stand-alone, purpose-built temperature and RH dataloggers, as opposed to data from building management systems or spot-checking instruments, provides the greatest degree of control, accuracy, access to the data, and analysis potential.

When placing dataloggers in the collections environment for optimization analysis, the key is to monitor locations where the data will document the overall behavior of the environment and/or the effect of any mechanical system on that environment. In various cases the condition of a microclimate within the space, such as suspected cold temperatures along an exterior wall or a damp corner, may be monitored as part of the process. When dataloggers are limited, the priority should be to choose a logging location that will record how space conditions respond to strategic adjustments. Data should be retrieved for analysis regularly, both to observe the effects of seasonal changes on the environment as well as to monitor and confirm any operational changes to the mechanical system or environmental control that are made for energy purposes during the experimentation phase.

Though datalogging in collections spaces is a common practice, a key feature of IPI's approach, and critical to the analysis of energy usage and savings, is the instrumentation of multiple locations within the mechanical system and air loop. Most systems consist of

one or more components that expend energy to either condition the air or move it to and from the physical zone that the system serves. By recording the air conditions at each of these components, common monitoring locations include the return, outside, mixed, cooled, and supply (heated) air streams, we can measure the change in condition, in degrees Celsius, imparted either by the energy-using component or by the blending of two air sources. When caused by a component, that temperature change can be converted to energy in British thermal units (Btus); once converted to the billing unit used, whether for tons of chilled water or kilograms of steam, the monetary expenditure for that energy can be calculated. Logging the amperes used by electrical components such as supply and return fans and electrical heating coils provides the energy consumption of the component, which, in combination with the component's time of operation, can either be converted into kilowatts or kilowatt/hours, typical billing units for electrical supply. Calculating the energy usage in the system over the course of a year provides a baseline marker that serves as the comparison for modeling and assessing new operations.

Step three: data analysis

Analysis of the space data is performed at two levels, an initial troubleshooting analysis of the graphed data each time it is retrieved, and a more in-depth preservation analysis for assessment of the baseline and adjusted environments. Analysis at the graph level yields quick information regarding both space conditions in relation to programmed control set points, as well as the physical operation of the mechanical systems. Seasonal changes in temperature or RH that are influenced by the outdoor climate are often noticeable at the graph level, while changes that are due to a change in the system-controlled set point appear as more immediate variations. Periodic temperature variations may indicate the presence of a mechanical system setback or shutdown, or a schedule for overhead lights. Comparing a dew point plot from the space data to the outdoor dew point can indicate the ability of a mechanical system or the building envelope to control moisture compared with the outside environment. The tendency of systems to have a dew point signature comparison creates a useful method of determining which spaces are served by which systems when comparing a series of indoor dew point plots. RH data that spans several years can indicate the presence or lack of humidification equipment, but also the level of operation from year to year if the humidifier is present. This initial analysis allows the process team to rapidly assess the preservation environment in a space without immediately moving to preservation analysis.

IPI's methodology then relies on applying the raw data to our series of algorithms, referred to as the IPI Preservation Metrics™. These yield quantitative estimates of how the observed conditions in the space promote or retard such general mechanisms as the kinetics of spontaneous chemical change in organic materials, mold growth, mechanical damage in hygroscopic materials and metal corrosion. Such estimates allow for the comparison of the preservation quality of different environments, whether from one storage area or mechanical zone to another, or from one set of temperature and relative humidity conditions in a space to other possible choices for the same space. One of the most important keys to good climate management is to know when to emphasize the needs of specific objects or object types
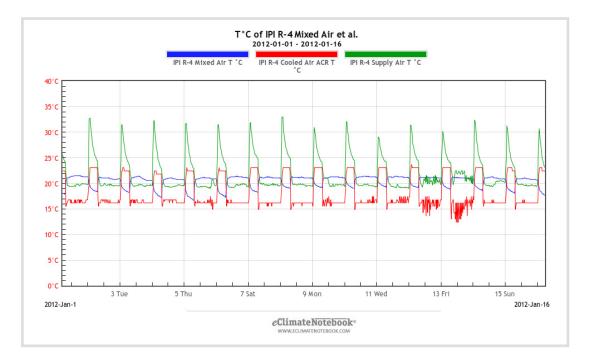
Figure 3. Temperature data from within a mechanical system can reveal sub-optimal operation. In this graph, the data shows incorrect sub-cool and reheat behavior during winter months when no dehumidification is necessary. While the space does require some cooling year round, in this case the mixed air enters the unit, is sub-cooled below the necessary supply air temperature, and then reheated to achieve that supply temperature when a small amount of cooling was all that was needed. Visible spikes in the cooled and supply air conditions are due to the heating coil valve failing to close during system shutdowns

rather than concentrate on the general preservation quality of the environment. Our experience has been that a balance of the relative needs and metrics is the best choice when making climate management decisions for mixed collections. Specific decay categories, such as chemical or mechanical change, may be concentrated on when a collection type is relatively homogenous.

In addition to using the data logged from the mechanical system for initial energy analysis, the process team can also use that data to analyze and inspect the behavior of each component in the system. Each component and process should be examined with three overarching questions at stake:

• what preservation climate is the existing system actually delivering on an annual basis;
• what preservation climate is the existing system capable of delivering on an annual basis;
• and is the system using more energy than necessary to deliver the actual climate?

Inefficient operation in the mechanical system is typically not self-announcing; conditions in the preservation environment may be perfectly satisfactory. Common energy-wasting practices that do not self-announce can include unnecessary sub-cool and re-heat operation (meant for dehumidification) during dry winter months (Figure 3), running variable frequency drives on fan motors at a constant speed and incorrect usage of face and bypass dampers

AHU #1:

The best-case scenario for AHU #1, without capital improvements, is to:

- Correct the current year-round sub-cool/reheat operation to only sub-cooling when dehumidification is necessary (May–October)
- Run an 8-hour shutdown of the system nightly
- Use the current summer setpoint of 65°F and roughly 58-60% RH
- Enact winter, non-dehumidification, season (November–April) setpoints of 60°F and 35-40% RH.

This will provide an improvement in the preservation environment conditions by slightly decreasing the rate of chemical decay and by reducing physical damage, while resulting in the following total costs:

Supply Fan	*Cooling Coil*	*Heating Coil*
$6,385 (31% savings over as found cost)	$5,048 (47% savings over as found cost)	$2,517 (69% savings over as found cost)

in a system. Cumulatively, such practices can lead to energy waste of up to 30 % or more over the course of a year; the same environmental conditions could have been produced for a fraction of the energy.

By trending and analyzing data from the collections spaces before making any experimental adjustments to the storage environment or system operation, the team has a baseline of the normal preservation environment and system operation to serve as a point of comparison and can debate the merits of various improvement strategies. Graphs and the Preservation Metrics™ allow for both visual and quantitative comparisons of conditions, and the assessment of what improvements might be desirable in the preservation environment in both preservation quality and seasonal conditions.

Step four: experimentation and implementation

With documentation of the collections spaces, systems, and building complete, and baseline data and analysis in hand, the process team can begin to explore the fourth step: experimentation with and implementation of various strategies to improve the preservation quality of the collections environment, reduce energy consumption, or shift energy usage patterns to achieve a reduction in energy costs. Some strategies will become apparent simply through analysis of the data. Heating an unoccupied collections storage area to 21 °C throughout cool winter months not only harms the overall preservation environment, but is also likely to be quite energy intensive. Allowing that space to drift to a seasonal set point of 10 °C would both improve the quality of the preservation environment as well as save energy. Flat-line control of RH at 50 % plus or minus 5 % is energy intensive year-round; if the collections in question can withstand fluctuation between 30 % and 60 % RH, energy savings could be achieved with a minimal effect, and perhaps an improvement, on some rates of collections decay.

Other options for altering preservation environments and mechanical operation often depend on having experience with energy-saving methods and a detailed knowledge of control systems and their programming. Methods such as shutdowns, setbacks, adjustment of operating modes, the reduction of outside

air and/or the use of economizers often require both the flexibility and the accountability of modern control systems as well as a knowledgeable controls operator who understands how best to apply the logic to the system, making their involvement in the process, particularly in larger institutions, ideal. In some cases, such as incorrect sub-cool and reheat operation, energy-saving adjustments can be made with little to no risk to the preservation environment. Others, such as shutdowns, require detailed assessment of the potential risks involved. If those risks are acceptable or manageable, the process team can move forward with careful experimentation, reviewing and assessing the impact on the preservation environment and energy consumption before continuing.

Before any permanent changes are implemented, one significant role of the process team is to gauge the potential consequences of that action and determine whether they are in the best interests of the institution, for both preservation and energy considerations (Figure 4). The team's experience with documentation and data gathering allows for open discussion of the positives and negatives of each strategy; energy savings at the expense of preservation is not the goal, nor is it improved preservation by increasing energy consumption. Changes should be experimented with and implemented one at a time in order to accurately assess the consequences of each adjustment, not only in terms of the preservation environment and energy, but also any impacts on the building or human comfort. If the change is satisfactory to the entire team, the next adjustment can be addressed.

Step five: assessment and maintenance

Once changes to the environment and system operation have been implemented, two stages of assessment follow: assessment of each individual change after several weeks' to a month's operation, and continuing assessment of the total impact of all changes over time. In both cases, strict comparison can be difficult; the baseline data for the preservation environment and energy usage are dependent upon a series of variables, ranging from system operation to changing outdoor climate conditions to potentially undocumented or uncontrollable changes in practice or utilities. Nonetheless, the impact should still be roughly quantifiable. Energy usage of the implemented changes can be weighed against what was measured as a baseline, and the documentation inspected for any additional factors beyond the change that could have influenced the outcome. Assessment of preservation quality can be more difficult, and often requires a longer period of review, particularly when the modeled impact is minimal. Changes in seasonal operation, for example drastic improvements in preservation environments during cooler months, may show immediate change when first assessed, with that impact evening out as time passes into other seasons and operational set points. The actual preservation impact of a shutdown or setback may be much harder to quantify if it only results in a minor fluctuation in the space. If the change results in significant documented energy savings, the difficulty in gauging the impact of the change may imply that the change was worthwhile.

Maintenance of optimal practice is the final significant piece of the process. Monitoring the environment and the systems should continue, with periodic evaluation of both the raw data and the quantitative assessment of preservation and energy to gauge

whether the practices are continuing appropriately. System operations and controls have a tendency to change unexpectedly, whether due to mechanical failure, planned maintenance, miscommunication, or any number of other factors that may change behavior. Systematic review, and the continuation of both documentation and communication among the process team are necessary to ensure that optimal operation continues.

Conclusion

Achieving an optimal preservation environment has the potential to both improve collections preservation as well as reduce energy consumption. The process of working toward that goal may also yield improvements in communication among stakeholders. Establishing efficient operations can lead to new, simple targets for the environment and systems that result in greater staff efficiency, and the institution can take pride in the accomplishment and improve their public and professional image. Our experience has shown that, while there is no specific condition or operation that is optimal for every institution, every institution has the opportunity and need to make appropriate changes that will bring it closer to optimal. This methodology, tested by IPI in various iterations among several research and fieldwork partners, is still in development, but the modeled and measured results of the process give every indication that the optimization of preservation and energy consumption is not only desirable, but also obtainable.

References

[1] Sebera, D., Isoperms: An Environmental Management Tool, the Commission on Preservation and Access, Washington, D. C. (1994).

[2] Reilly, J.M., Nishimura, D.W., and Zinn, E., New Tools for Preservation: Assessing Long-Term Environmental Effects on Library and Archives Collections, the Commission on Preservation and Access, Washington, D. C. (1995).

[3] Mecklenburg, M.F., Determining the Acceptable Ranges of Relative Humidity and Temperature in Museum and Galleries, Smithsonian Museum Conservation Institute (2007), http://www. si.edu/mci/downloads/reports/Mecklenburg-Part1-RH.pdf.

[4] Bigourdan, J.L., 'Understanding temperature and moisture equilibration: a path towards sustainable preservation strategies', Presentation to Indoor Air Quality 2012: 10th International Conference, Indoor air quality in heritage and historic environments London 17 – 20 June 2012, Indoor Air Quality, London (2012), https://www.imagepermanenceinstitute.org/ webfm_send/605 (accessed 19 April 2013).

Authors

Jeremy Linden joined the Image Permanence Institute (IPI) as a preservation environment specialist in January 2010. Email: jrlpph@rit.edu

James Reilly is the founder and Director of the Image Permanence Institute at Rochester, Institute of Technology in Rochester, New York, a world leader in preservation research since 1985. Email: jmrpph@rit.edu

Peter Herzog, of Herzog/Wheeler & Associates, LLP, is an architect, engineer, author, and teacher. He has a long and distinguished career in energy management process design, technical analysis of energy-consuming processes and systems, troubleshooting, and energy conservation planning. Email: peter-herzog@msn.com

Evaluation of different approaches of microclimate control in cultural heritage buildings

Tor Broström, Tomas Vyhlídal, Goran Simeunovic,
Poul Klenz Larsen and Pavel Zítek

Abstract

The objective of this paper is to evaluate different approaches to microclimate control in historic buildings in relation to the requirements for indoor climate and energy consumption. The conventional methods are examined: passive microclimate control, humidity control and humidistatic heating; and compared with two novel control strategies: equal-sorption humidity control and natural climate fluctuations control. Starting from a general overview of the methods based on the state of the art and experience from selected case studies, the methods are evaluated using building simulation software.

Introduction

The issue of sustainable management of the indoor climate in historic buildings has received considerable attention in the last decade. The main motivations for this are the increase in energy costs and the demand for improving conditions in historic buildings where cultural heritage is stored. An important factor to be considered in indoor-climate management is the increasing number of visitors to historic buildings. When seeking to define suitable microclimate conditions, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and the European EN15757 standards can be considered. In ASHRAE, the microclimate conditions for various types of historic buildings are defined by taking into consideration the material characteristics of the stored objects [1]. The European Standard EN15757 determines the target ranges and variability of microclimate conditions (temperature and relative humidity) for organic hygroscopic materials [2].

The results presented in this paper have been achieved in the project Climate for Culture, particularly in work-package 7, which focuses on mitigation, adaptation and preservation strategies in historic interiors. The main objective of this paper is to evaluate different approaches to microclimate control with respect to their applicability in historic buildings and their energy demands. The methodology used will provide inputs to a decision support system being developed in the project Climate for Culture. In the investigation, the conventional methods of passive microclimate control, humidity control and humidistatic heating are outlined, and compared with two novel control strategies, equal-sorption humidity control and natural climate fluctuations control. The evaluation is based on a compilation of the scientific literature, experiences from selected case studies in the Climate for Culture project and simulation-based tests. The methods are then evaluated and compared using building simulations applied to a model of the Holy Cross Chapel at Karlstejn Castle.

Passive microclimate control

Many historic houses and their interiors have survived for centuries without any active climate control. Examples of such buildings are the seventeenth-century castle at Skokloster near Stockholm [3] and Linderhof Palace near Munich, a nineteenth-century royal summer residence [4]. These buildings rely entirely on the natural stability provided by their structure and geometry. The hygrothermal inertia depends mainly on the thickness of the walls and their composition, the interiors and the air exchange rate. The building will ameliorate the diurnal fluctuations in temperature and relative humidity (RH). The indoor climate in a building with only passive control is thus decided by the building itself and the outdoor climate. In practice, the passive controls can be enhanced by regulating the air exchange by opening chimneys and ventilation ducts or by sealing the windows and doors. Any active solution for climate control in historic buildings should be based on an understanding and utilisation of the passive function of the building.

Humidity control

Humidity control is performed by releasing water vapour to the air if the RH is too low (humidification), or by removing water vapour from the air if the RH is too high (dehumidification). There are two methods of humidification, injection of steam into the air, or evaporation of water or water mist. Evaporation cools the air, so supplementary heating is required to keep temperatures constant. Humidifiers can either be permanent installations with ducts and water pipes, or moveable devices with a water reservoir.

Dehumidification is a commonly used method for decreasing high values of relative humidity in historical buildings. Within recent years dehumidification has been adapted for energy efficient climate control in cultural heritage buildings in Denmark [5]. There are two methods for dehumidification, condensation and adsorption. An adsorption dehumidifier requires an air duct to remove moist air from the building to the outside. The adsorption dehumidifier can operate at low temperatures, even below zero degrees. The condensing dehumidifier requires a bucket or a drain to collect and remove condensate. The condensing dehumidifier is not efficient below 8 °C, because ice is generated on the cooling unit, so intermittent defrosting is required.

The applicability of dehumidification in historic buildings depends on whether the technical installations are acceptable with respect to both visual and physical impact. Portable dehumidifiers allow for flexible and cost-effective solutions but often the machinery is not well suited to a historic environment. A system of central dehumidification can be better integrated but it requires air ducts. Unless the building already has air ducts, the installation tends to be expensive and intrusive.

Humidistatic heating

Humidistatic heating, or conservation heating, is the concept of heating a building in order to keep the relative humidity below given limits. The temperature is continuously adjusted and not controlled to a constant set point. Humidistatic heating has been used for many years to maintain a moderate relative

humidity in historic houses in winter [6]. It is a simple and robust climate control strategy. The functionality depends on building characteristics, hygrothermal inertia, insulation, air tightness, the air infiltration rate and the temperature control. A peculiar aspect of humidistatic heating is that heating may sometimes be required in summer in order to keep the RH at an acceptable medium level. This may cause uncomfortably high temperatures and high energy consumption [7]. Generally an increased temperature will increase the absolute humidity in the building [7] causing an unwanted positive feedback. Degradation of organic materials due to hydrolysis will increase with temperature and RH growth.

Humidistatic heating can be implemented in any building with permanent or temporary heating installations at moderate costs. The energy consumption for humidistatic heating is relatively high, due to poor thermal insulation and a high infiltration rate. In a case study on three historic buildings owned by the National Trust, the annual energy consumption for heating was 39 – 53 kWh/m^3 [8]. A comparison of conservation heating and dehumidification in Denmark [5] shows that the most energy-efficient control strategy is determined by the U-value of the building, the air exchange rate (AER) and the volume of the building. Generally, dehumidification is more energy efficient, unless heat pumps are used. An air-to-air heat pump will typically reduce energy demand by two thirds. For large buildings, humidistatic heating with heat pump technology seems to be the most energy efficient approach unless the thermal insulation is very poor. For small buildings, dehumidification is more efficient unless the building is very leaky.

Equal-sorption humidity control

One of the main tasks of preventive conservation is to prevent moisture sensitive materials from anisotropic swelling or shrinking caused by changes in the absorbed moisture content. This objective is targeted in the equal-sorption humidity control method proposed by Zítek and Vyhlídal [9]. The method takes into account the influence of temperature on the sorption isotherms, which is usually neglected in common climate control. For most materials the moisture content is slightly reduced at rising temperatures, even if the RH is kept constant. It is therefore acceptable to have a higher RH in summer than in winter. Although the moisture content compensation is dependent on particular material properties, it has been shown that the difference can be neglected for most types of organic hygroscopic materials [9]. The stabilisation of moisture content in the objects is implemented by humidity control. In order to determine the nominal set point value of relative humidity based on current temperature, the logarithmic Henderson model describing the equilibrium moisture content [10] is used.

As demonstrated by Zítek et al. for wooden materials, the relationship between moisture content and material strain can be utilised to determine the allowable variations of relative humidity from its nominal set point value [11]. Based on moisture content and material strain characteristics reported in the literature, 1.25 % are the safe variations of moisture content from the quasi-equilibrium value, which transfers approximately to variation of 7 % of RH [12 to 14]. Under these variations, only elastic deformations should take place in the layers of wooden material.

In practice, the implementation of the equal-sorption humidity control method requires modification of the humidity control system; the RH set points for humidifier and dehumidifier depend on the current temperature (more details are provided in the appendix). The first implementation of the equal-sorption control principle has been in operation in the microclimate control system of the Holy Cross Chapel in Karlstejn Castle since 2000. The method was then implemented in the low-cost humidity control system in the Historica collection of Archives in Trebon Castle [9].

Natural climate fluctuations control

The last microclimate control method to be discussed is a concept motivated by the specifications defined in the European Standard EN 15757 [2]. The standard proposes algorithms for controlling relative humidity, which take into consideration characteristics of both the historic and actual natural climate oscillations. Thus, there is no fixed set point or range for RH values for dehumidifiers (and humidifiers if they are available). The set points are automatically adapted to meet the control requirements in relation to seasonal averages rather than an absolute range. According to the Standard EN 15757 [2], see also [13], the target range of relative humidity is determined based on the fluctuation from the 30-day central moving average. Consequently, the acceptable range of relative humidity fluctuations from the moving RH average value is determined as the 7th and 93rd percentiles of the fluctuations recorded in the monitoring period, which is at least one year. If the relative humidity records are not available, the allowable fluctuations are considered as 10 % RH.

Based on the specifications described above, a natural climate fluctuations control (NCfC) method has been proposed and studied [15]. In particular, the filtering and other necessary algorithms for the set point adjustment for (de)humidifiers have been designed and analysed using simulation software. For example, the central moving average filter, which is non-causal and cannot be used in real-time applications, is substituted by a simple moving average filter. For the practical implementation of the method, existing climate control systems, heating or humidity control, can be used with some modification of the control system.

However, it is extremely important to stress that as a preliminary step to the application of this control approach, the historic climate should first be verified as safe for the collection or the moisture-sensitive furnishings. If this is not the case, the relative humidity ranges should be adjusted accordingly, based on recommendations by an expert. For example, the method can be supplemented by the strict upper and lower limits on the RH set points.

Evaluation and comparison of the control methods using Building Simulation software

The evaluation and comparison of the microclimate control methods was performed with a simulation model of the Great Tower of Karlstejn Castle, which is one of the case studies in the Climate for Culture project. Karlstejn (Figure 1) is a large Gothic castle, about 30 km southwest of Prague, founded in 1348 by Charles IV, the Holy Roman Emperor and the most famous King of Bohemia. It was built to house the Imperial and Bohemian crown jewels and a precious collection of holy reliquaries. Karlstejn is

Figure 1. View of
Karlstejn Castle
dominated by the
Great Tower

one of the most famous and most frequently visited castles in the Czech Republic.

One of the most valuable parts of the castle is the Holy Cross Chapel in the Great Tower (Figure 2). On the Chapel's walls, there is a precious collection of outstanding wood panel paintings by Master Theodoricus from the period of 1360 to 1365. The set of paintings is one of the most notable collections of medieval art and also the largest collection of a single artist from the fourteenth century in the whole of Europe. Since 2000, the chapel has been equipped with a special local air-handling system adjusting the internal microclimate to prevent the paintings and other exhibits from deterioration by moisture impact [11, 16].

The Great Tower has six floors and the Holy Cross Chapel is located on the third floor. All outer walls have a similar structure but vary in thickness, from 1.1 metres to 6.3 metres. The parameter model of the Great Tower of Karlstejn Castle was constructed in Matlab - Simulink using the HAMBASE tools [17]. The model consists of seven zones, each room of the Great Tower is represented by one zone. In the simulation model, the influence of visitors on the indoor microclimate is also considered. The model has been tuned and validated to the existing indoor and outdoor climate measurements.

Coupled with the HAMBASE model of the Great Tower, the following climate control strategies have been implemented in Matlab-Simulink for a model of the Holy Cross Chapel:

- Humidity control (HC), target range 40 to 65 %
- Humidistatic heating (HH), set point: 65 % RH. Maximum temperature: 25 °C
- Equal-sorption control (ESC)
- Natural climate fluctuations control (NCfC)
- Passive climate control (no active climate control).

With the exception of passive climate control, a minimum temperature of 10 °C is maintained in the winter season. This is motivated by specific conditions in the castle.

Simulation results

The results of the simulations are shown in figure 3 for interior temperature, and figure 4 for interior relative humidity. The results from using passive controls only will serve as a reference. With no active climate control, RH levels approach 100 % in the summer which is also due to the influence of visitors. Thus, RH control is a

Figure 2. Interior
of the Holy Cross
Chapel at the Great
Tower of Karlstejn
Castle

critical issue for the chapel. The temperature follows the seasonal variation of the outdoor climate. Humidistatic heating keeps RH below the specified level of 65 % but at the cost of a high interior temperature well above normal comfort levels, particularly in spring and autumn. When temperatures increase above 25 °C, the heat is turned off causing a few shorter time periods above the target range. As there is no humidification in the winter season, RH drops to levels near 30 %. Humidity control (HC) keeps RH in the given range (here from 40 to 65 %) with no significant effect on temperature.

The equal-sorption humidity control (ESC) method keeps the RH within the 14 % band centred at the RH value determined from the

Figure 3. Simulated indoor temperature in the Holy Cross Chapel located in the Great Tower of Karlstejn Castle (HC - humidity control, HH - humidistatic heating, ESC - equal-sorption humidity control, NCfC - natural climate fluctuations control)
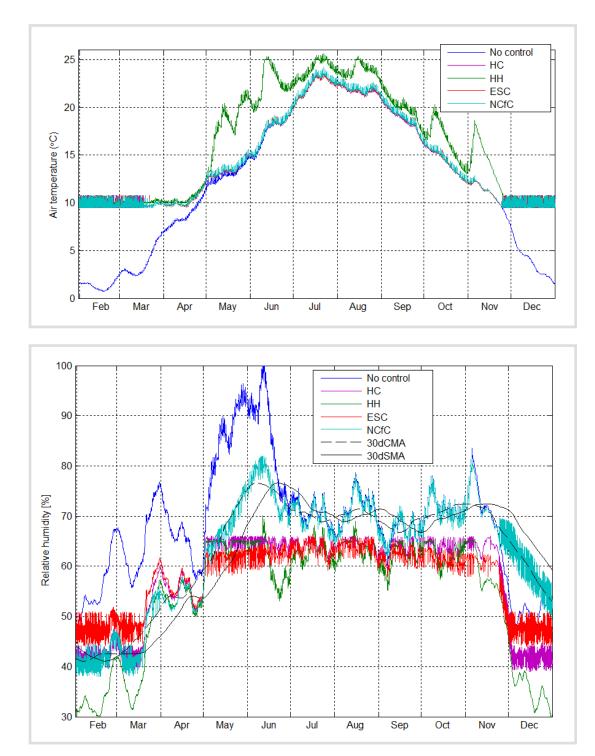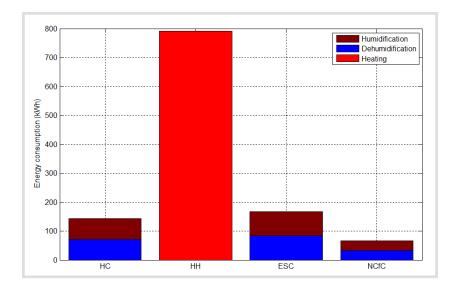

Figure 4. Simulated indoor relative humidity in the Holy Cross Chapel located in the Great Tower of Karlstejn Castle (HC - humidity control, HH - humidistatic heating, ESC - equal-sorption humidity control, NCfC - natural climate fluctuation control, 30dCMA – 30 day central moving average, 30dSMA – 30 day simple moving average)

Henderson model based on actual temperature in the interior. The influence on temperature, as compared to passive control, is small.

Natural climate fluctuation control reduces short-term variations of relative humidity in relation to the moving average of RH, as shown in figure 4. However, it needs to be considered that the RH controlled by this method results in quite high values in the summer season (from 70 to 80 %), which can be considered as unsafe by other standards (e.g., ASHRAE [1]). As demonstrated, the results of the simple moving average are shifted by 15 days from the results of the central moving average, which should be considered in control implementation. The considered algorithms of the RH control methods are outlined in more detail in the Appendix.

As one of the main results, we provide a comparison of energy consumption between the RH control methods, shown in figure 5. The energy consumption of background heating to 10 °C is 1346 kWh. In figure 5, this value is subtracted from the overall energy consumption so that only the energy needed for humidity control is shown. As is evident, humidistatic heating is by far the least effective method for controlling RH, this would be true even if a heat pump were used. On the other hand, the natural climate fluctuation control would have the lowest energy consumption results. The energy demands for humidity control and equal-sorption humidity control are at about the same level.

Conclusions

The results presented here can provide guidance for adjusting the climate control strategy in a particular historic building. The methods presented are generally applicable and could be used for any building in any region. In the simulated example of controlling the microclimate in the Holy Cross Chapel of Karlstejn Castle, the overall objective was to achieve a moderate relative humidity all year. Passive climate control would not be acceptable by any standard. The variations in RH are too large, both in the short and long term, and there are long periods of excessively high RH. Humidistatic heating should only be implemented if there is a need for human comfort. A heat pump should be used to achieve a reasonably energy-efficient solution. Auxiliary dehumidification would be needed in the summer to avoid uncomfortably high

temperatures and to keep RH at safe levels. Equal-sorption control with dehumidification and humidification gives the most stable conditions for the moisture-sensitive objects (wooden panel paintings). However, the difference when compared to conventional humidity control is relatively small. The energy consumption for both cases is comparable. Natural climate fluctuation control provides RH stability in the short term, but seasonal variations and high levels of RH are problematic. In this case, the control algorithm needs additional conditions to address long-term variations and high levels of RH. This would reduce or eliminate the advantage in terms of energy consumption, shown in figure 5. As the different approaches have different control targets, there are no optimal solutions based on quantitative data. For the example given, the primary options would be equal-sorption control, humidity control and an augmented natural climate fluctuation control. This kind of methodology will be used in the Climate for Culture project, applied to generic buildings in order to provide decision support in all regions of Europe.

Appendix – Algorithm specifications of the control methods used in the simulation example

In all the methods, a heating system which keeps the temperature above 10 °C was considered. The relay based on-off control is applied with hysteresis plus/minus 0.5 °C. Next, except for the humidistatic heating, both the humidifier and dehumidifier are available for controlling relative humidity according to the generated set points using relay based on/off algorithm with hysteresis plus/minus 2 %.

Humidity control

The set point for the humidifier is φ_H = 40 % and the set point for the dehumidifier is φ_D = 65 %.

Humidistatic heating

If the RH is above 65 %, the heater is on and it operates in order to decrease RH levels until the temperature is below the upper temperature limit 25 °C. If the temperature is outside of this limit the heater is turned off regardless of the RH level.

Equal sorption humidity control

The set points of relative humidity for the humidifier is given by

$$\varphi_H(T_f) = 100\left[1 - \left(1 - \frac{\varphi_0}{100}\right)^{\frac{T_f+B}{T_0+B}}\right] - 7$$

and the set point for dehumidifier is

$$\varphi_D(T_f) = 100\left[1 - \left(1 - \frac{\varphi_0}{100}\right)^{\frac{T_f+B}{T_0+B}}\right] + 7$$

Where φ_0 [%], T_0 [°C] is a selected reference air state given as a combination of relative humidity and temperature satisfying

the preventive conservation regulations, T_f [°C] is the actual (measured) interior temperature filtered with a second order Buterworth filter (with the aim to filter out fast changes of temperature) and the parameter B [°C] is a parameter of Henderson model (for wood Bϵ [60, 100] °C). Here we consider φ_0 = 52 %, T_0 = 16 °C and B = 70 °C.

Natural climate fluctuation control

The simple moving average is used instead of the central moving average filter. The reason for this adaptation is that the central moving average cannot be used in real time applications as the 15-day future data are needed for evaluating the current value of filtered RH. The different form of the simple moving average

$$\phi_{-30}(k) = \phi_{-30}(k-1) + \frac{1}{2N}\big(\varphi(k) - \varphi(k-2N)\big)$$

is applied, where ϕ_{-30} [%] is the output of the filter, i.e., the filtered value of RH, φ [%] is the measured RH, N = 360/Δt is the number of samples covering 15 days with the sampling period Δt [hour]. The set point values are determined as
$\varphi_{D,\ SET}$ (k) = φ_{-30} (k) + B_D for dehumidifier and
$\varphi H_{,\ SET}$ (k) = φ_{-30} (k) – B_H for humidifier,
where B_H, B_D [%] determine the desired allowable fluctuations of relative humidity from the actual moving average ϕ_{-30}. Based on the evaluation of the yearly fluctuations from central moving average, both the values are determined as B_H = B_D = 8 %. The final set point values are further adjusted by an active feedback to control the growth rates of the RH set points (more details are provided in [15]).

Acknowledgements

References

[1] American Society of Heating, Refrigeration and Air-Conditioning Engineers, 'Museums, libraries, and archives', in ASHRAE Handbook - HVAC Applications, ASHRAE, Atlanta: Georgia (2003) 21.1–21.16.

[2] European Standard, EN15757 Conservation of Cultural Property - Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials (2010).

[3] Broström, T., and Leijonhufvud, G., 'The indoor climate in Skokloster Castle', in Historical Buildings as Museums. Systems for Climate Control and Heritage Preservation, ed. D. Del Curto, Nardini Editore, Florence (2010) 84–93.

[4] Bichlmair, S., and Kilian, R., 'Room climate in Linderhof Palace. Impact of ambient climate and visitors on room climate with special focus on the bedchamber of King Ludwig II' in Developments in Climate Control of Historical Buildings. Proceedings from the international conference "Climatization of

Historic Buildings, State of the Art". Linderhof Palace, December 2nd 2010, ed. R. Kilian, T. Vyhlídal, T. Broström, Fraunhofer IRB, Verlag (2011) 49–55.

[5] Larsen, P.K., and Broström, T., 'Climate control in cultural heritage buildings in Denmark', in Developments in Climate Control of Historical Buildings. Proceedings from the international conference "Climatization of Historic Buildings, State of the Art". Linderhof Palace, December 2nd 2010, ed. R. Kilian, T. Vyhlídal, T. Brostrom, Fraunhofer IRB, Verlag (2011) 39–44.

[6] Staniforth S., Hayes, B., and Bullock, L., 'Appropriate technologies for relative humidity control for museum collections housed in historic buildings. Preventive humidistatic: practice, theory and research', in Preprints of the Contributions to the Ottawa Congress, 12–16 September 1994, Preventive Conservation: Practice, Theory and Research, ed. A. Roy and P. Smith, International Institute for Conservation, London (1994) 123–128.

[7] Larsen, P. K., 'Climate control in Danish churches', in Museum Microclimates, Contributions to the Conference in Copenhagen 19–23 November 2007, ed. T. Padfield, K. Borchersen, The National Museum of Denmark, Copenhagen (2007) 167–174.

[8] Blades, N., Poupard, S., and Barber, L., 'Analysing the energy consumption of humidistatic heating systems at the National Trust', Journal of the Institute of Conservation 34.1 (2011) 16–27.

[9] Zítek, P., and Vyhlídal, T. 'Model-based moisture sorption stabilization in historical buildings', Building and Environment 44.6 (2009) 1181–1187.

[10] Avramidis, S., 'Evaluation of ''three-variable'' models for the prediction of equilibrium moisture content in wood', Wood Science and Technology 23.3 (1989) 251–257.

[11] Zitek, P., Vyhlidal, T., Sladek, O., Sladek, A., and Simeunovic, G., 'Equal-sorption microclimate control applied to the Holy Cross Chapel at Karlstejn Castle', in Developments in Climate Control of Historical Buildings. Proceedings from the international conference "Climatization of Historic Buildings, State of the Art". Linderhof Palace, December 2nd 2010, ed. R. Kilian, T. Vyhlídal, T. Broström, Fraunhofer IRB, Verlag (2011) 57–65.

[12] Jakiela, S., Bratasz, Ł., and Kozłowski, R., 'Numerical modelling of moisture movement and related stress field in lime wood subjected to changing climate conditions', Wood Science and Technology 42 (2008) 21–37.

[13] Bratasz, Ł., 'Acceptable and non-acceptable microclimate variability: the case of wood', in Basic Environmental Mechanisms Affecting Cultural Heritage, ed. D. Camuffo, V. Fassina, J. Havermans, Nardini, Florence (2010) 49–58.

[14] Camuffo, D., Microclimate for Cultural Heritage. Elsevier Science Ltd., Amsterdam, London (1998).

[15] Vyhlidal, T., and Broström T., (ed.), 'New algorithms for optimal control of the relative humidity and temperature using equal-sorption humidity control as well as approaches including

combinations of active and passive climatisation', Deliverable report D7.1 of the Climate for Culture project (2012).

[16] Nemecek M., and Papez, K., 'Uprava vzduchu v historickych, objektech', Vytapeni, vetrani, instalace 10.4 (2001) 50–158.

[17] Schijndel, A.W.M. van., Integrated heat air and moisture modeling and simulation. PhD thesis, Eindhoven: Technische Universiteit (2007) (unpublished).

Authors

Tor Broström is Professor in Conservation at Gotland University. He is a specialist in energy efficiency and indoor climates in historic buildings. Email: tor.brostrom@hgo.se

Poul Klenz Larsen is a senior consultant at the National Museum in Copenhagen, working mainly with climate control in churches and historic buildings. Email: poul.klenz.larsen@natmus.dk

Tomas Vyhlídal is a Professor at the Department of Instrumentation and Control Engineering at the Czech Technical University (CTU). He is also a leader of the work package on mitigation adaptation and preservation strategies for the Climate for Culture project. Email: tomas.vyhlidal@fs.cvut.cz

Goran Simeunovic is a researcher at the Department of Instrumental and Control Engineering at CTU in Prague. Email: goran.simeunovic@fs.cvut.cz

Pavel Zítek is head of the Department of Instrumentation and Control Engineering at CTU in Prague. Some of his most recent work involves researching humidity and moisture sorption problems in the preventive conservation of cultural heritage. Email: pavel.zitek@fs.cvut.cz

Licence

A critical look at the use of HVAC systems in the museum environment

Edgar Neuhaus

Abstract

Complex heating, ventilation and air conditioning (HVAC) systems are often used in museums to optimise the indoor climate for preservation and visitors' comfort. In practice these systems regularly do not function according to their design specifications. As a result the indoor climate for preservation can be even worse than if the system were not used. For example, high daily relative humidity fluctuations can occur due to malfunctioning equipment or faulty control strategies; furthermore unexpectedly high energy use can occur due to too strict climate boundaries being pursued and mistakes made during the design phase. The functioning of a HVAC system should therefore not be trusted blindly but some level of caution should be taken. Monitoring indoor climate conditions independently from the HVAC system is essential.

Illustrated by various cases taken from Dutch practice, this paper tries to raise awareness among collection managers, curators, restorers and other museum professionals. The most frequently encountered problems with HVAC systems in the museum environment are described and general recommendations are given to avoid, detect and resolve these problems. This paper is not intended to discourage the use of complex HVAC systems since when designed, controlled and maintained properly, these systems can offer a great contribution to the preservation of cultural heritage.

Introduction

Preventive conservation can be described as a process that seeks to prevent, reduce or mitigate the effects of factors that threaten the continued survival of collections. An incorrect relative humidity (RH) or temperature, high levels of dust and gaseous pollution are some of these threatening factors that can be reduced by using mechanical systems. Inappropriate values of temperature and RH are often less dramatic than, for example, the risk of fire or theft, but nonetheless pose a serious problem for the conservation of heritage. The approximately 800 registered museums in the Netherlands, of which around 90 % are housed in historic buildings, are therefore often equipped with air-handling units (AHUs).

In cases with high visitor numbers, often vast HVAC systems are needed primarily to bring in enough fresh air for visitors' health and comfort. These are typically museums with a highly-prized collection or historic house museums with a small air volume. Due to financial reasons, often a maximum annual amount of visitors is desirable, so large HVAC-systems are installed to provide enough ventilation rather than limiting the amount of visitors.

Besides providing fresh air and thermal comfort for visitors and staff, these machines are intended to control environmental

influences for preventive conservation. Figure 1 shows a simplified representation of how a typical AHU in a museum works. The building management system (BMS), a computer-based control system, controls the mechanical components of the AHU and is connected to sensors in the exhibition space and sensors in the AHU. Depending on the conditions of the outside air and return air and what the desired inlet condition is, the BMS decides whether the supply air should be cooled, heated, humidified or dehumidified. Additionally the air is filtered in the AHU. It has to be noted that more and finer filter packages lead to a substantially higher energy use because of a greater pressure loss which has to be compensated by the supply fan.

From the 1980s onwards confidence in mechanical system began to grow and the feeling prevailed that all climate risks could be excluded. Controlling the RH as tightly as possible was considered the best course. Guidelines with a strict allowable bandwidth for RH were based on the mechanical limitations of the HVAC system rather than on collection needs. These tight boundaries for temperature and RH often resulted in the assembly of vast and energy-guzzling equipment.

It is only relatively recently that scientific research has provided a basis for determining appropriate values for the museum climate, particularly the range in which temperature and RH can be safely allowed to vary [1, 2, 3]. This more object-oriented approach, based on chemical, physical and mechanical properties of materials, is now becoming more widely acknowledged and more rational environmental standards or guidelines are beginning to emerge. The decline of the financial climate, more scientific information becoming accessible and the reduction of reliance on fossil fuels ('going green'), have certainly played a role in this transition.

However, countries in western Europe still tend to focus on optimising the indoor climate primarily by active means, meaning mechanical systems are favoured over, for example, architectural features. Passive means to optimise the indoor climate, for example, building physical measures, can be considered as more durable and reliable but are often disregarded. There may be various reasons for this situation, for example, it may be illegal to change the aesthetics of the protected historical building, or because the proposed measures do not comply with the architect's vision. Mechanical systems are then needed to compensate for the lack of proper sun shading or insulation, or to remove the great
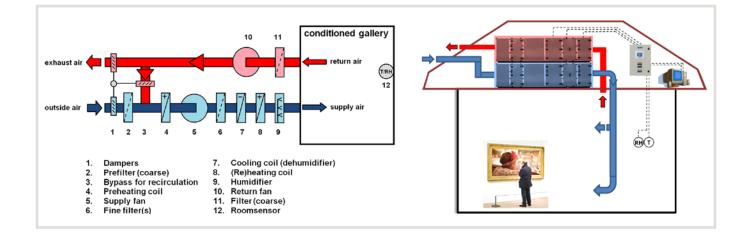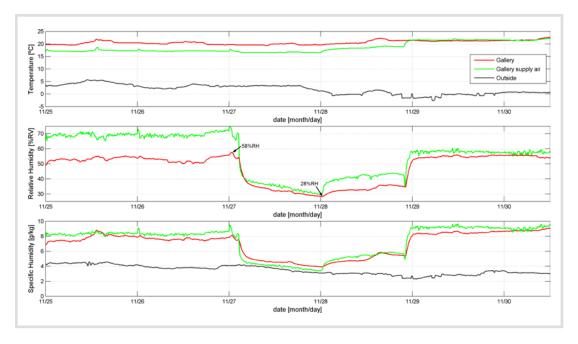
Figure 1. A simplified representation of how an air-handling unit in a museum works. The picture on the left shows a schematic view of the main components. The picture on the right shows a museum with an AHU and connected ducts. The AHU is controlled by the computer-based building management system

conditioned gallery

exhaust air
outside air
return air
supply air

1. Dampers
2. Prefilter (coarse)
3. Bypass for recirculation
4. Preheating coil
5. Supply fan
6. Fine filter(s)
7. Cooling coil (dehumidifier)
8. (Re)heating coil
9. Humidifier
10. Return fan
11. Filter (coarse)
12. Roomsensor

heat load due to large glass facades in newly built architecturally-sound museums.

In practice, installed HVAC systems often do not function properly, leading to unnecessarily high energy consumption and maintenance costs. In some museums the climate can even be more disrupted and unstable than without having a climate system, posing a threat to the conservation of artefacts on display and the historic building structure itself.

Methods

In various museums equipped with an AHU and facing climatic problems, research is performed in order to optimise climate conditions for preventive conservation. This research typically consists of three steps. The first step is collecting climate data (temperature and RH) of indoor air, outdoor air and supply air for a minimum of a several weeks. The shortcomings of the equipment can often be made visible with this data by simply calculating and comparing the specific humidity of outdoor air, indoor air and supply air.

The next step is to analyse the building and HVAC characteristics. During a global inspection, information is gained about, for example, the level of insulation, level of airtightness, orientation of the exhibition spaces, type of air distribution, type of cooling system and level of air recirculation. The collected climate data can be better interpreted with this additional information. In addition, the functioning and configuration of hardware and control systems are inspected, including important field sensors. The last step consists of analysing the collected data and trying to attribute the shortcomings detected to specific components of the system.

Common problems
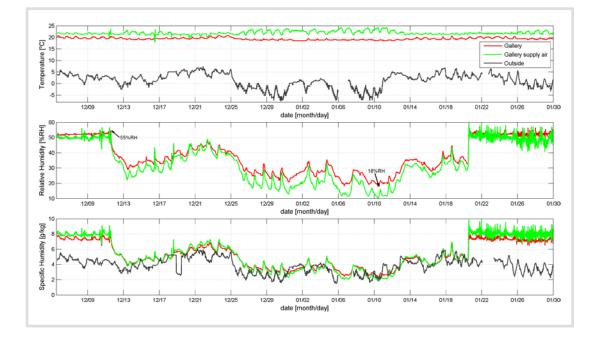
Based on experiences from Dutch practice collected over the past five years, the three most common problems are described and analysed here.

HVAC-system malfunctions, causing a large disruption in RH

If one of the components of a climate system malfunctions, temperature and RH control can easily be disrupted. For this observation we need to distinguish two types of malfunctions.

The first type can be described as an acute but usually short-term malfunction, for example, the malfunctioning of a steam humidifier in an AHU that conditions 100 % outside air. During periods of frost outside, air can contain very little moisture. RH fluctuations of 25 % or more within a few hours can occur when outside air is only heated, filtered and then supplied to a room (Figure 2).

The malfunction shown in figure 2 was relatively quickly remedied. In this case the failure was instantly detected due to built-in alarm functions in the building management system and the adequate response of the people responsible. However, this situation could have had less climatic impact if two humidifiers had been installed which could be switched over automatically by the building management system for runtime balance and during failure mode. Redundancy, the duplication of critical components for increased reliability, is therefore essential for HVAC-systems in museums with climate-sensitive collection. This concept also includes keeping spare parts of failure-prone components on site. Examples of such components are fan belts and steam cylinders for humidifiers. Furthermore it should be noted that if the set-point for temperature and RH had been seasonally adjusted, the difference between specific humidity of indoor air and outdoor air in this particular case would have been less, resulting in a smaller RH fluctuation in the event of a malfunction.
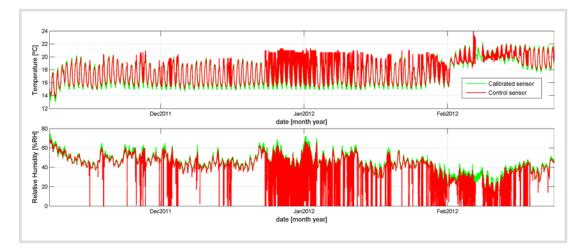
Large disruptions of the museum climate can also occur during maintenance. Annual periodic maintenance should therefore preferably be scheduled during the intermediate seasons, in which the difference between the specific humidity of the inside and outside air is relatively small. During these seasons the specific humidity of the outside air in the Netherlands ranges between 5 to 10 g/kg in general.

Figure 3. An example of a long-term RH drop due to malfunction of the humidification system which was not detected instantly, recorded in a Dutch museum. RH in the gallery drops from 50 % down to values as low as 17 %. It took 39 days before the system was eventually fully operational and the room RH was restored

The second type of malfunction can be described as a long-term erroneous functioning of the system. This can mostly be attributed to ineffective monitoring of the functioning of the system or ineffective monitoring of the indoor climate conditions by incompetent staff or maintenance firms. Long-term malfunctioning is best illustrated by the unfortunate event that happened in the storage facility of the Ancient Art Museum in Brussels in 2009. During the winter season, the humidification system for the museum storage area malfunctioned, resulting in a RH drop which was only discovered after 55 days. By that time hundreds of the 842 stored paintings were damaged, mostly suffering from problems with the paint layer, with estimated restoration costs of 1 million Euros [4]. Figure 3 shows the indoor climate conditions in an exhibition space for a similar situation, recorded in 2009 in a Dutch museum. Apart from a relatively long period in which hygroscopic collections will desorb moisture, two critical RH fluctuations occur; once when the humidifier stops working and once when the humidifier is repaired. In this case it might be better to slowly rebuild the moisture level to the set RH, instead of 100 % capacity in a very short time.

Another issue that can lead to long-term incorrect functioning of an AHU is the result of defective room sensors or control sensors. These sensors usually do not automatically generate an alarm in case of breakdown or faulty behaviour, and in the best case are inspected and calibrated once a year. Figure 4 shows data sent to the BMS by a faulty control sensor, compared with data collected with a calibrated stand-alone sensor. The faulty data led directly to an incorrect functioning of the AHU. Important system sensors therefore should be checked regularly. It is highly recommended that data are collected with an independent monitoring system where sensors are also placed near to the system's control sensors.

Figure 5 shows a disrupted museum climate caused by errors in the BMS. In this particular case, erroneous and unstable control signals led to an incorrect functioning of AHU components and an unstable room temperature and RH. Due to errors, the set-point of inlet temperature was locked and the control of the cooler was unstable. The situation was restored by replacing a defective circuit board in the BMS. These problems can often only be discovered and resolved by in-depth inspection of the system, analysing control systems and configuration of the BMS.

Incorrect system selection or design

An incorrect system selection can be observed in various museums. Systems unsuitable for the museum environment can create stable climate conditions close to the room sensor, but with very unstable conditions in the vicinity of collection objects, or they can cause large hygrothermal stratification [5, 6, 7]. Examples of this are systems where supply air is not being fully mixed in the room or inlet grilles are inconveniently positioned. Figure 6 left shows a thermal image of a gallery where the supply of conditioned air takes place at floor level, causing warming up and drying of paintings which are hung directly above the floor grilles. Figure 6 right shows an exhibition space with a radiant floor heating system. During the heating season the floor temperature can be 5 °C warmer than the average room air temperature. This means that if the space is conditioned to e.g. 20 °C/50 % RH, objects placed on the floor will experience a RH of about 37 % or even lower near the contact area and could possibly suffer damage due to desiccation.

The position of the control sensors in the exhibition room is of great importance as this will determine the condition of the supply air. The best position of the control sensors is close to climate-sensitive collection objects. It is regularly observed that control sensors are positioned in the return air duct, sometimes far away from the exhibition room and very near to the AHU. Temperature and RH in a duct 20 or 30 metres away from the exhibition room, however, can differ from room conditions, thus a deviation is created, particularly in systems with a variable air-flow.

Unrealistic and unnecessarily strict demands

The third problem encountered with HVAC-systems in the museum environment is the result of an overly strict set bandwidth for temperature and RH. Historic buildings are often poorly insulated
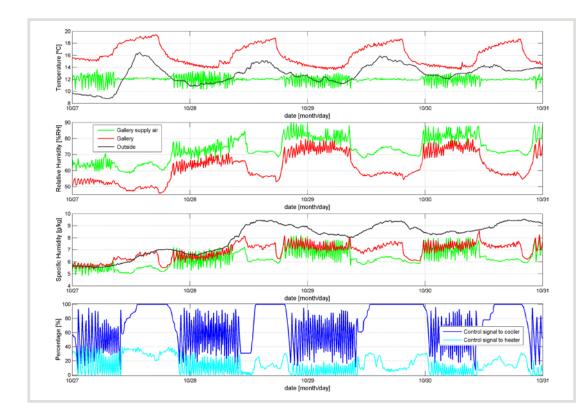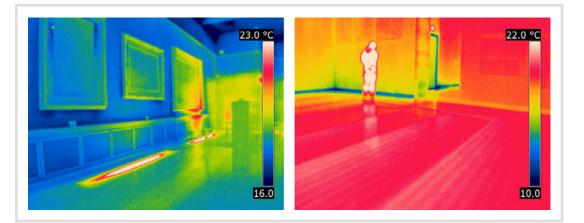
Figure 5. In this particular case erroneous control signals were sent to the AHU by the BMS due to a defective circuit board

and quite leaky. When applying tight RH control in such buildings problems occur mostly during the winter. It can be commonly observed that there is heavy condensation on single glass panes, leading to leakage in the exhibition room, mould growth and rotting of wooden window frames. While spatial RH can be perfectly level at 50 %, RH near cold walls can be much higher. Figure 7 shows a thermal image of a painting against an uninsulated wall during winter. Whilst RH in the room is about 50 %, RH behind the painting is well over 75 %. In this case, the collection could be at risk due to possible long-term very high RH in winter [8]. During periods with very low external temperatures, in some cases condensed water can be observed running down the interior face of exterior walls from behind paintings. This problem can be significantly reduced or even avoided by just slightly lowering the set value for the room temperature and the set RH. Whereas a set point of 20 °C/50 % RH has a dew point of 9.3 °C, a set point of 18 °C/45 % RH has a dew point of 5.9 °C. Therefore, in air-conditioned poorly-insulated buildings collection should not be placed against outside walls, or spacers should be used to keep an air space between walls and paintings.

How these problems occur and can be avoided

HVAC-systems in the museum environment are different from systems in office buildings. Here 24-hour operation is required and systems therefore need to be robust and reliable. Spare vital components, such as humidifiers, should be kept in reserve, so that in case of malfunctioning or maintenance disruption of climate conditions will be limited. Air distribution should be well mixed, to avoid stratification and to promote homogeneous climate conditions. Depending on possible sources of pollution in the building, as much air as possible should be recirculated and outside air should be the minimum amount required to provide fresh air for visitors. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) handbook [7] describes the various systems that are applicable for controlling temperature, RH and airborne pollutants in the museum environment in more detail.

Control of the system should be incorporated in a building management system which is, to some level, accessible by the user. Data from (room) sensors and control signals to the systems components should be logged by the BMS. Data that should be visible to the user at any time are: RH in the exhibition spaces and the temperature and specific humidity of outdoor air, supply air

Figure 7. Example of a seventeenth-century painting hung on an un-insulated external wall in a museum that is conditioned to 20 °C and 50 % RH. The thermal image shown left, is taken during wintertime. Clearly visible is the cooler surface under the painting. The right image shows a hygrograph with the calculated surface RH of the same situation. It can be expected that the RH behind the painting is well over 75 %

and room air. Registered temperature and RH should be coupled to an automated alarm function, so that in the case of specific values exceeding or undershooting a set bandwidth, an alarm, via email or text message, is generated to the museum's facility manager or directly to the maintenance company.

As well as monitoring via the BMS, it is essential to monitor indoor climate conditions with a stand-alone wireless monitoring system that is also capable of generating alarms if conditions fall beyond the desired boundaries.

The problems as described above are often also caused by the fact that HVAC designers primarily focus on thermal comfort (temperature-control) and often have limited knowledge or experience with controlling RH. Collection managers, conservators and facility managers often lack a (basic) knowledge of building physics and HVAC systems and are therefore not always adequately able to adjust proposed HVAC plans. An interdisciplinary collaboration with the appropriate specialists from the early stages of a renovation project or the new build of a museum is essential.

Conclusion

This paper highlights common problems when using HVAC-systems in the museum environment. The Dutch experience indicates that expensive HVAC systems are no guarantee for having optimal climate conditions for preventive conservation. Malfunctioning equipment or faultily designed systems can cause heavily disrupted climate conditions near collections and can even decrease the lifetime for exposed or stored objects. Malfunctions can occur due to an erroneous control strategy or defects in hardware. In the museum environment critical HVAC-components should be kept in reserve, and the system should have a comprehensive self-check and alarm function for detecting malfunctioning components or sensors. Indoor climate conditions should be monitored constantly, not only by the building management system but also by an independent monitoring system, which automatically generates alarms if conditions are out of range. Some types of HVAC-systems might successfully be applied in settings other than museums or storage facilities, but might not work when RH control and homogeneous indoor conditions have precedence over temperature control.

A significant amount of attention should be given to optimising the physical structures before bringing in mechanical systems. Building physical measures to optimise the indoor climate can be

considered as being more durable and reliable and preferable to mechanical systems. An example of this is effective sun shading or adequate thermal insulation. Mechanical systems should be regarded as a last resort.

For new-build museums or storage facilities the design phase is critical to achieve an optimal indoor climate. An interdisciplinary design team consisting of an architect, engineers, conservators, collection managers and security staff should be carefully selected at the very start of the project so the right knowledge and expertise are brought together.

Recent literature shows that the indoor climate in most museums is unnecessarily tightly controlled. When a museum or storage facility is newly built or being renovated the collection should be thoroughly assessed first. What climate boundaries and fluctuations are actually safe for this specific collection? For most objects RH fluctuations do not pose a large risk, as long as they are gradual, within certain boundaries, and at values where chemical and biological degradation are not imminent. Sensitive objects could possibly be placed in display cases in which the local environment can be more closely controlled, rather than conditioning the whole building's air volume.

Unfortunately, museums are still being built or renovated with a prescribed HVAC system designed to maintain RH in the exhibition space at 50 % plus or minus 1.5 % the whole year round, without taking account of the fact that standard measurement equipment has uncertainties greater than the specified range. HVAC systems can be designed on a smaller scale if temperature and RH are allowed to vary during the year, saving substantial costs in terms of equipment, energy, personnel and maintenance.

Acknowledgements

References

[1] Erhardt, D., Tumosa, C.S., and Mecklenburg, M.F., 'Applying science to the question of museum climate', in Contributions to the Museum Microclimates Conference in Copenhagen 19–23 November 2007, ed. T. Padfield and K. Borchersen, The National Museum of Denmark, Copenhagen (2007) 11–17.

[2] Bratasz, Ł., Kozłowski, R., Łasyk, Ł., Łukomski, M., and Rachwał, B., 'Allowable microclimatic variations for painted wood: numerical modelling and direct tracing of the fatigue damage, in ICOM Committee for Conservation, 16th Triennial Conference Preprints, Lisbon Portugal, 19–23 September 2011, ed. J. Henderson, ICOM-CC, London (2011) 1–7.

[3] Martens, M.H.J., Climate Risk Assessment in Museums, Eindhoven University of Technology (2012).

[4] Binst, B., 'Dalkia schadedossier en course', http://www.brusselnieuws.be/artikel/dalkia-schadedossier-en-cours (accessed 9 August 2012).

[5] Neuhaus, E., Aarle, M.A.P., Pernot, C.E.E., and Schellen, H.L., 'Displacement ventilation in the museum environment, a case study', in Proceedings of the 10th Clima World Congress Sustainable Energy use in Buildings, Antalya Turkey, 10–12 May 2010.

[6] Neuhaus, E., Ankersmit, B., and Schellen, H.L., 'Radiant floor heating in museums, research after hygrothermal gradients', TVVL Magazine, 40.11 (2011) 10–15 [in Dutch].

[7] American Society of Heating, Refrigerating and Air-Conditioning Engineers, 'Chapter 23, Museums, Galleries, Archives and Libraries', in ASHRAE Handbook – HVAC Applications (SI), ASHRAE, Atlanta (2011) 23.1–23.22.

[8] Mecklenburg, M.F., 'Micro climates and moisture induced damage to paintings', in Contributions to the Museum Microclimates Conference in Copenhagen 19–23 November 2007, ed. T. Padfield and K. Borchersen, The National Museum of Denmark, Copenhagen (2007) 19–25.

Author

Edgar Neuhaus is a private consultant specialising in optimising the museum climate for preventive conservation. Email: e.neuhaus@physitec.nl

Licence

The role of historic house heating systems in collections climate control at the National Trust

Nigel Blades, Hazel Jessep and Katy Lithgow

Abstract

This paper describes the rationale for the National Trust specification for environmental control and how conservation heating as a control strategy developed from an appreciation of historic heating methods. Current methods used by the National Trust to assess environmental data from a large number of buildings are described, and an evaluation of damage functions as a new and improved approach to understanding environmental data is presented.

Introduction

In the early 1990s the National Trust for England, Wales and Northern Ireland developed conservation heating as its preferred climate control strategy for mixed collections on open display in historic interiors [1]. The aims of this strategy were to prevent high relative humidities (RH) that support biodeterioration and, conversely, to avoid low RH that causes desiccation, shrinkage and cracking of organic materials, as well as to reduce fluctuations to acceptable levels.

This paper describes the National Trust environmental control standard, its rationale and how we are using the latest research and data analysis tools to better understand the impact of the environment on collections.

National Trust environmental control specification

The National Trust standard for environmental control [2] is for RH to be maintained between 40 and 65 % for 90 % of the time over a calendar year. Temperature is considered to be of secondary importance and is modified by conservation heating to control RH by the psychrometric relation of temperature and RH, resulting in a wide range of room temperatures, typically 5 to 25 °C.

The upper RH limit of 65 % was adopted primarily as a threshold for mould growth. Much of the scientific literature suggests that the threshold for most moulds is about 70 to 80 % RH [3], but the limit of 65 % was found to work well in historic houses as it allows for the difference between measurement of the bulk room environment and cooler microclimates close to external walls in showrooms, as well as providing for sensor inaccuracies. By maintaining room RH below 65 %, we aspire to keep the coolest parts of a room below the more widely recognised 70 to 80 % RH mould threshold.

The lower RH limit of 40 % recognises current thinking that the majority of collections can tolerate RH anywhere in the range of 40 to 60 % [4]. The National Trust standard does not specify the rate of change within the 40 to 65 % RH band; it is assumed that for most materials, fluctuations within this band will be tolerable.

Moreover, National Trust historic houses tend to be thermally massive structures that experience slow changes in environmental conditions.

The 40 to 65 % control band is not expressed as an absolute, but rather statistically, with the aspiration that it should be met for 90 % of the time in a calendar year. Random excursions are not considered dangerous, but any concerted periods of low or high RH could be damaging and are investigated. The 90 % performance target takes into account climatic limitations on conservation heating. In humid summer weather in the UK, it is difficult to reduce RH below 65 % with heating, because the temperatures required can be greater than 25 °C, which make showrooms uncomfortably hot for visitors. To avoid overheating, and to conserve energy, conservation heating is operated with a 22 °C upper temperature limit in the summer and an 18 °C limit in the winter. This means conservation control can be lost for approximately three to six days a year in the warmest south-east corner of the UK, with other parts of the UK being less affected.

Excursions below 40 % RH can occur naturally, for example, in warm dry spring weather, which can cause low RH (30 to 40 %) inside historic houses, even with the heating turned off.

The Trust's policy in re-servicing heating systems in properties with collections or significant historic interiors is to add conservation control to maintain conditions between 40 to 65 % RH.

Role of heating systems in determining environmental conditions in National Trust houses

Understanding historic heating and its development and use informs our understanding of the historic environment of collections and interiors. The National Trust has been studying historic heating installations as part of its Country House Technology project [5]. The main theme of this research to date has been the study of technology through surviving installations in Trust houses. In the present paper we combine this research with data from early heating manuals and textbooks [6] to establish the likely heat outputs from nineteenth-century systems; we also apply computer building simulation to estimate temperatures and relative humidities that might have pertained in a mansion house in the late nineteenth and early twentieth centuries.

Before the nineteenth century, rooms would have been unheated or heated only by open fires. Stoves were used relatively rarely in English houses, compared with elsewhere in Europe. The nineteenth century saw the beginnings of central heating, first by ducted warm air and occasionally by high-pressure steam. Later in the nineteenth century these systems were superseded by piped hot water systems and, from the 1870s onwards, radiators [6]. Whilst the latest technologies and hot water heating systems were often embraced by householders and installed widely through the late nineteenth/ early twentieth centuries, a number of properties came to the Trust with heating by open fireplaces alone, or with no heating at all in some rooms.

Thus, collections in a typical National Trust house might have experienced a progression of heating regimes, from no heating in many rooms and open fires in occupied spaces, to increasingly

powerful central heating systems, initially with coal-fired boiler and gravity (thermosyphon) hot water circulation, and then, from the 1920s onwards, oil-fired boilers and pumped circulation.

It is difficult to generalise about the impact of radiant heat from an open fire on room RH. Our properties show that whilst a cooking range in a small kitchen can provide sufficient heat to significantly lower room RH, a fire in a great hall fireplace has little measurable effect on RH. Previous research using building simulation [7] has suggested that open fires have a much smaller effect on room RH than central heating.

In order to understand the impact of early central heating on room environments we have undertaken a building simulation exercise, based on Dyrham Park House (Figure 1). Consulting Engineers Buro Happold Ltd were commissioned to model the effect of the existing installed radiators working with a coal-fired boiler and gravity circulation (thermosyphon) system. An intensive heating schedule was modelled with the boiler running continuously from October to April, as would have been necessary to maintain thermosyphonic water flow. It was assumed that the boiler fire would be banked overnight, reducing output to 25 % and that during the daytime a flow temperature of 165 °F (74 °C) could be maintained (as specified by Victorian heating engineers [6,8]). Since the building fabric of Dyrham has remained largely unchanged from the nineteenth century it is reasonable to assume that the thermal performance of the building captured in the simulation is a fair representation of its performance in Victorian times. Open chimneys were included in the model but fires were not simulated. Two ground floor rooms, the Great Hall (10.7 kW installed radiator power), Drawing Room (2.2 kW) and one first floor bedroom (1.1 kW) were modelled in detail using the Integrated Environmental

Figure 1. Dyrham Park (large) and the IES Building Simulation Model (small) constructed of the mansion property by Buro Happold. Only the main mansion, shown in yellow, was simulated with the Victorian heating regime. The rooms simulated were the Drawing Room, located behind the three ground floor windows at far left; the Great Hall, set back in the middle of the building with south-facing window; and the Bedroom, behind the three windows at far right on the top floor.

Solutions (IES) building simulation package. The remainder of the mansion was set to a background temperature of 16 °C. Test reference year climate data for the nearby town of Swindon were used as the weather input.

Historic heating systems and relative humidity
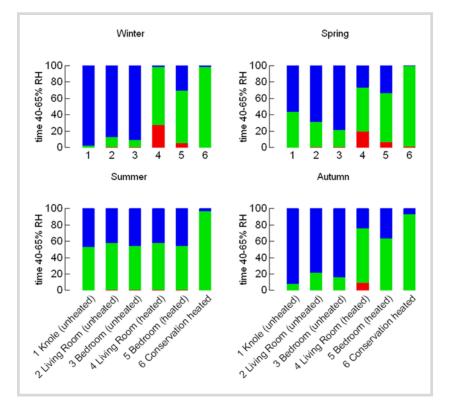
The results of the building simulation suggest that on all but the coldest days, the heating would be able to a maintain 18 °C in the Great Hall and Drawing Room and 13 °C in the Bedroom. This is in agreement with Victorian design criteria, which recommended design temperatures of 60 to 65 °F (16 to 18 °C) in living rooms when outside conditions were 30 °F (-1 °C) [8].

Figure 2 shows the RHs resulting from the modelled late nineteenth/ early twentieth century central heating on living room (4) and bedroom (5) environments, compared with unheated rooms (1 to 3). The heating effect is beneficial, with RH mostly in the 40 to 65 % range. However, in (4) the heating is sufficiently powerful to give significant episodes of low RH (less than 40 %) in the winter months that could cause desiccation and cracking of hygroscopic materials such as furniture and panels. In (5) where the installed heating power is less, this effect is almost eliminated. Naturally occurring high summer RH is observed in both (4) and (5), when the heating is switched off. Data from a conservation-heated room (6), the Long Gallery at Ham House illustrate the humidistatic control achieved by a system operating continuously through the year so that periods of high summer RH can be mitigated.

To summarise, high RH conditions would have been prevalent in the early history of houses, leading to biodeterioration but probably avoiding the mechanical damage associated with low RH. The introduction of central heating systems in the late nineteenth and early twentieth centuries would have significantly

Figure 2. RHs likely to have been experienced by historic house collections under different heating regimes: (1) Knole, Brown Gallery, unheated, measured data 2008; (2) Dyrham Park Drawing Room and (3) Dyrham Park Bedroom simulated without heating, and with heating in (4) and (5). A conservation-heated room, the Long Gallery at Ham, is included for comparison (6). Data are shown in relation to the National Trust environmental control standard: blue for values greater than 65 % RH, green for values between 40 to 65 % and red for values less than 40 %.

reduced room RH and may have caused desiccation and damage where heating was sufficiently powerful. If installed heating power was relatively small, or heating was turned off to save money, the effect was likely to be mainly beneficial in reducing biodeterioration.

Over their lifetime, National Trust collections might therefore have experienced relative humidities in the range 30 to 80 %. Thus our current desired band of 40 to 65 % RH reflects average conditions that might have been experienced historically, whilst avoiding detrimental extremes.

Methods of assessing environmental performance in National Trust properties

The previous sections described the basis of the National Trust's environmental control standard. Currently, performance against this standard is measured through annual reporting of control statistics for each property. An annual environmental control performance indicator (PI) score is established for each room with collections (calculated by the percentage of time that RH falls within 40 to 65 %), and an overall property PI score is calculated as the 25th percentile of all room performances. For instance, if the property PI score is 60, this would mean that three quarters of its rooms maintained RH 40 to 65 % for 60 % of the year or better, whilst one quarter of the rooms had RH 40 to 65 % less than 60 % of the year. Thus, the PI score gives a measure of the quality of control achieved in the majority of rooms.

The aim of this assessment is to highlight, in conjunction with collections condition monitoring, where resources for preventive conservation should be targeted. While giving a broad overview of conditions at each property, this method does not differentiate between potential risks to organic collections from different causes, nor does it take into account the magnitude or duration of excursions outside the 40 to 65 % RH band.

New tools for evaluating RH risk

New climate risk assessment tools are under development, utilising the latest research on damage functions for organic materials. These offer the possibility of more accurate analysis of climate risks to collections. The next part of our paper investigates the application of this approach to National Trust collections. The climate risk assessment tools tested were developed by Marco Martens and a team at the University of Technology Eindhoven [9, 10].

Case study selection and data gathering

To assess the effectiveness of these tools in predicting risks within historic houses, we selected case study properties representative of both the environmental conditions and types of interior and collection found in the Trust's historic houses. Recent data illustrative of the long-term environmental conditions within the rooms of each property were analysed. The risks predicted from the damage functions were then compared with existing National Trust control metrics, as described above, and condition assessments from a random sample of organic objects from each room, to establish any correlation between the environmental
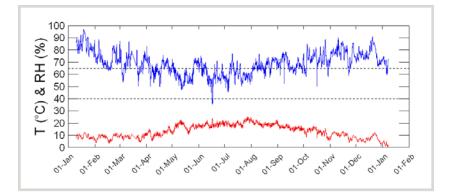
Figure 3. Knole House, environmental data for the Brown Gallery, January – December 2008. Temperature is shown in red and RH in blue. Over this 12-month period the RH was within the National Trust 40 to 65 % RH control band for 33 % of the time. The overall RH control performance indicator score (defined as the 25th percentile of all collections rooms annual time within 40 to 65% RH band) for Knole in 2008 was 30.
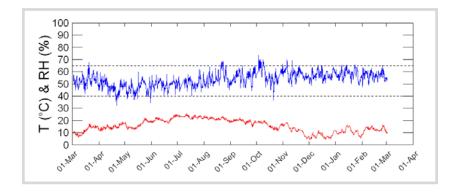
Figure 4. Ham House, environmental data for the Long Gallery (north), March 2010 – March 2011. Temperature is shown in red and RH in blue. Over this 12-month period the RH was within the National Trust 40 to 65 % RH control band for 97 % of the time. The overall RH control performance indicator score (defined as the 25th percentile of all collections rooms annual time within 40 to 65 % RH band) for Ham in 2010-11 was 90.
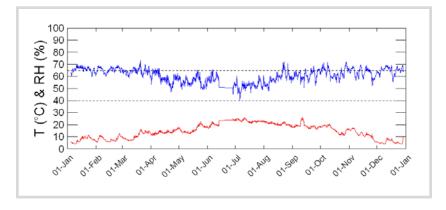
Figure 5. Ightham Mote, environmental data for the Old Chapel, January – December 2010. Temperature is shown in red and RH in blue. Over this 12-month period the RH was within the National Trust 40 to 65 % RH control band for 72 % of the time. The overall RH control performance indicator score (defined as the 25th percentile of all collections rooms annual time within 40 to 65 % RH band) for Ightham Mote in 2010 was 60.

conditions experienced and patterns of observed deterioration. Three properties were selected to test the analytical tools, with similar mixed collections but different levels of environmental control.

Knole House, Kent is built around seven courtyards in Kentish Ragstone, with timber-framed upper storeys, where most of the showrooms are located. Environmental control is not installed apart from in the Great Hall, where the wet system radiators are humidistatically controlled to 58 to 60 % RH; the King's Room which has an electric radiator operated from a humidistat; and the Museum Room, which is dehumidified. Environmental conditions are generally considered to be unsatisfactory in most of the showrooms (Figure 3).

Ham House, Surrey was built of brick in 1610, on a Jacobean H-plan with two projecting wings to north and south. Later alterations added rooms to the centre section. An extensive conservation heating system with electric water-filled radiators is installed in most showrooms, controlled by a Trend Building Management system (BMS) with wall-mounted sensors. Showrooms are controlled to 58% RH according to the standard National Trust specification [2]. The system was installed in the early 1990s and continues to deliver good environmental control (Figure 4).

Ightham Mote, Kent is a moated manor house built around a single courtyard in Kentish Ragstone, with timber-framed upper storeys to the north, south and east ranges. Conservation heating is controlled by a Trend BMS, operating zone valves for a wet heating system powered by an electric storage boiler and Hanwell humidistats operating on water-filled electric radiators. Environmental control is considered moderately satisfactory, but not ideal, given the generally small installed heating power and the rapid heat loss characteristics of the building (Figure 5).

Figure 6. Left: the Spangled Bedroom at Knole; Right: Long Gallery at Ham House, showing the range of mixed organic collections at the two properties.

All three properties have collections and decorated wall and ceiling surfaces demonstrating a range of materials, from the organic (paintings, furniture, textiles and paper) to inorganic (stone and plaster). Knole has an important collection of Jacobean upholstered furniture, whilst the furniture at Ham House is decorated with lacquer and marquetry (Figure 6). Both collections

are considered fragile. The furniture collection at Ightham Mote is mainly carved, solid wood and more robust, but, like Knole, has fragile painted schemes on walls and ceilings.

Object condition assessments

In reviewing conservators' condition assessments it was important to differentiate between historic and recent occurrences of environmental damage on the sample objects, and to minimise the impact of different data recording practices: the condition recording varied both over time and between properties, with each object being assessed within the context of its collection. The detail recorded was greatest where objects were considered to be more fragile or important.

Analysis of the survey results
Biological deterioration

Table 1 presents the results from Knole and Ightham Mote, which have RHs frequently above 65 %, placing them at high risk of mould growth from the current National Trust metric. The isopleths tool developed by Sedlbauer considers the temperature, RH and time

| Knole House | | | | | Ightham Mote | | | | |
Room	Annual Average T (°C)	Annual Time % > 65 % RH	Isopleths Mould Risk Function	Objects examined with recorded mould growth	Room	Annual Average T (°C)	Annual Time % > 65 % RH	Isopleths Mould Risk Function	Objects examined with recorded mould growth
Lady Betty's Bedroom	14	56	Germination?	2 of 3	Oriel Room	15	25	safe	1 of 5
Spangled Dressing Room	12	77	23mm growth	4 of 7	Drawing Room	15	43	safe	0 of 10
Reynolds Room	14	48	Germination?	2 of 6	Great Hall	13	50	safe	0 of 6
King's Bedroom	15	32	Germination?	1 of 4	Sir James Bedroom	14	38	safe	0 of 6
Spangled Bedroom	12	72	14mm growth	1 of 6	Library	16	3	safe	0 of 6
Cartoon Gallery	13	55	Germination?	1 of 6	Old Chapel	15	28	safe	0 of 5
Great Hall	15	12	safe	1 of 6	Outer Hall	14	20	safe	0 of 5
Brown Gallery	13	67	10mm growth	1 of 7	Billiards Room	15	9	safe	0 of 5
Ballroom	13	51	Germination?	0 of 7	South Corridor	16	6	safe	0 of 5
Great Stairs	13	63	16mm growth	0 of 5	Jacobean Staircase	15	23	safe	0 of 4
King's Closet	14	58	safe	0 of 4					

Table 1. Environmental conditions at Knole and Ightham Mote, mould damage function predictions and comparison with observed mould growth. The damage function gives three possible results; safe, germination and a growth length, based on analysis of the environmental data. Condition records viewed for Ightham Mote date back to 2002/3, following the completion of major building conservation works, while the records viewed for Knole dated back to the late 1970s, however multiple instances of mould on objects have been recorded, including in the last decade. A single count of mould is recorded even if the object has been affected more than once within the period of time reviewed. Ham House has not been included on the table as the RH levels remain below 65 % and all rooms were predicted to be safe. Only two instances of mould were recorded across all rooms and these appear to be linked to water ingress or specific microclimates, similar to singular instances at Ightham Mote.

required for germination and then growth of mycelium on organic materials or accumulated particles on the surface that act as nutrition for fungi [3].

The isopleths results confirm a high risk of both mould germination and growth at Knole, while at Ightham Mote it suggested there is no risk of mould germination. These results correlated well with object condition surveys, with instances of mould growth in most rooms at Knole and the highest number

Knole House				Ham House				Ightham Mote			
Room	NT Spec 40-65 % range time met %	Decorative Furniture Function	Decorative furniture with mechanical deterioration	Room	NT Spec 40-65 % range time met %	Decorative Furniture Function	Decorative furniture with mechanical deterioration	Room	NT Spec 40-65 % range time met %	Decorative Furniture Function	Decorative furniture with mechanical deterioration
King's Bedroom	67	safe	4 of 4	Long Gallery North	97	safe	4 of 4	Drawing Room	58	safe	1 of 7
Spangled Bedroom	27	damage possible	3 of 3	Long Gallery South	96	safe	as above	Library	97	safe	0 of 3
Cartoon Gallery	45	safe	2 of 2	Duke's Dressing Room	96	safe	4 of 4	Oriel Room	75	safe	0 of 3
Spangled Dressing Room	23	damage possible	2 of 2	Duchess's bedchamber	87	safe	3 of 3	Sir James bedroom	62	safe	0 of 2
Brown Gallery	33	damage possible	1 of 1	Library Closet	80	safe	3 of 3	Outer Hall	79	safe	0 of 1
Ballroom	49	safe	3 of 4	North Drawing Room	98	safe	3 of 3	Jacobean Staircase	77	safe	0 of 1
King's Closet	42	safe	1 of 2	Withdrawing Room	91	safe	3 of 3	Old Chapel	72	safe	NA
Reynolds Room	52	safe	1 of 2	Library	95	safe	1 of 1	South Corridor	92	safe	NA
Great Stairs	36	damage possible	NA	Queen's Bedroom	95	safe	1 of 1	Great Hall	51	safe	NA
Lady Betty's Bedroom	44	safe	NA	Great Hall	94	safe	1 of 1	Billiards Room	60	safe	NA
Great Hall	88	safe	NA	Great Stairs	95	safe	NA				

Table 2. Environmental conditions at Ham, Knole and Ightham Mote, mechanical damage function predictions and comparison with observed damage on decorated furniture. The damage function gives only three possible results; 'safe', 'damage possible' and 'damage likely' based on analysis of the environmental data. The sample size includes only objects within similar characteristics to the object from which the damage function was developed, not the total number of objects surveyed within the room. NA means no objects with similar characteristics were found in that room for comparison. The recording of deterioration on objects was found to differ across the case studies in terms of level and type of detail included. In most instances records comprised of qualitative descriptions and accompanying sketches or images, limited quantitative information about the deterioration is recorded.

of affected objects in the room seen as at greatest risk (Figure 7). At Ightham Mote there was also good correlation, with only a single instance of mould growth across all the rooms (which was within an item of furniture, indicating the existence of a microclimate. Ham House (not shown in table 1) was predicted to be safe from mould growth, which correlated with observation. Overall, the more sophisticated damage function assessment proved to be more accurate as a mould predictor than simply considering for what percentage of time the RH exceeded 65 %. The use of measured bulk room conditions, either to calculate the damage function, or time above 65 % RH has the limitation that it cannot account for room or surface airflow or the existence of microclimates within a room. So, whilst full correlation was

	Spangled Dressing Room	Reynolds Room	King's Closet
Prediction of mould growth:	23mm growth	Germination?	Safe
% of objects with mould growth:	57 %	33 %	0 %
Time > 65 % RH	77 %	48 %	58 %
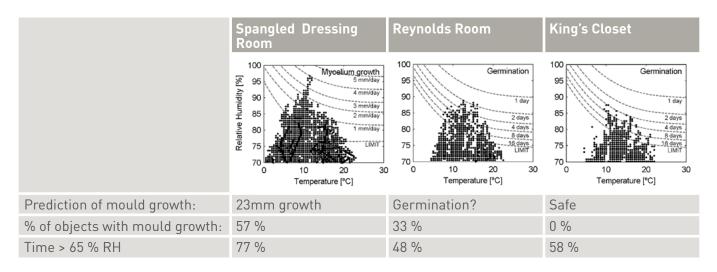
Figure 7. Mould growth isopleth charts generated by the University of Technology Eindhoven/Martens analysis tool (http://www.monumenten.bwk.tue.nl/) for the cases study rooms at Knole, with the corresponding mould predictions, percentage of affected sample objects and National Trust RH metric, show below each chart. The mould predictions are given as 'safe'.

	Spangled Bedroom, Knole	King's Bedroom, Knole	Long Gallery, north, Ham House
Prediction of mechanical damage:	Possible damage	Safe	Safe
% of decorative furniture with mechanical damage:	100 %	100 %	100 %
% time RH 40-65 %	27 %	67 %	97 %
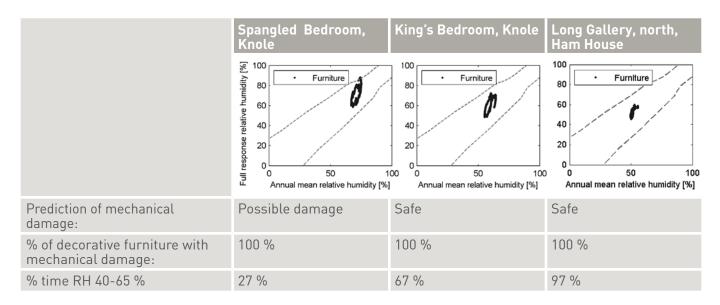
Figure 8. Three examples of the furniture mechanical damage charts produced by the University of Technology Eindhoven/Martens analysis tool (http://www.monumenten.bwk.tue.nl/) for cases study rooms at Knole and Ham, with the corresponding predictions and percentage of sample objects with signs of damage, and National Trust RH control metric shown below each chart. The prediction of possible damage appears to be due to the singular excursion, from the safe 'zone'. Whilst the fluctuations experienced in the Long Gallery at Ham House are less than those in the King's Bedroom at Knole both are considered to be safe.

not observed in all instances, the predicted risks were broadly accurate. It is also worth noting that where the damage function predicted a high risk of germination there was also a higher prevalence of damage caused by woodboring insects.

Mechanical deterioration

Table 2 presents the predicted risk of mechanical deterioration to decorative furniture, compared with the National Trust RH metric and the analysis tool mechanical damage function (Figure 8). This is based on research by Bratasz et al. [10] on the environmental response of a Japanese lacquered box from 1640. The case study property condition surveys included similar multi-layered objects with lacquer, gilt and marquetry, whose dimensional responses to RH fluctuation are expected to be different from their base timber material, leading to stresses in the objects and potential mechanical damage. The Ham and Knole collections are seen as very fragile and include many such vulnerable objects. The correlations between damage function, National Trust RH metric and observed damage were less clear than for mould growth. For instance, at Knole, eight of the showrooms had significant mechanical damage to objects. Whilst all of these rooms were unsatisfactory in terms of meeting the 40 to 65 % RH specification, five of the eight rooms were assessed 'safe' using the decorative furniture damage function, the other three being assessed 'damage possible'. At Ham the two data measures largely agreed, with nine of the 11 rooms meeting the 40 to 65 % RH control specification for 90 % of the time or better, the other two rooms scored in the 80s. The damage function gave all rooms as 'safe'. However, the condition assessments recorded mechanical damage on objects in all rooms at Ham. At Ightham Mote, of the six rooms with vulnerable furniture, only one met the 40 to 65 % specification for 90 % of the time, but all rooms were judged 'safe' by the damage function, which accords well with the observation of mechanical damage, found on only one object of 17 surveyed.

There may be a number of reasons for these discrepancies, such as the different approaches to condition assessment discussed above, and the great fragility of the Knole and Ham collections, making them vulnerable to degradation even in good environments. Another factor, particularly for Knole, could be loss of animal glue adhesive strength at RH above 75 % [11], which is not considered in the damage function. Nor do any of the data assessment methods take into account long-term acclimatisation of objects to specific environments.

Chemical deterioration

The damage function used in the analysis tool for chemical deterioration is the lifetime multiplier [12]. As chemical deterioration is rarely considered in National Trust conditions surveys, it was not possible to obtain any evidence of this type of deterioration from the sample of objects reviewed. However, it is interesting to compare the lifetime multipliers from the properties to see how deterioration might be predicted to progress over time. A median has been taken of average annual lifetime multipliers for paper across the rooms in each property for comparison with the baseline lifetime expectancy score of 1 (museum environment averages of 50 % RH and 20 °C). The median in Ham House was 1.41, Knole, 1.42 and Ightham Mote, 1.29. This suggests that

conditions in National Trust houses even where the RH is less than ideal, are better than expected in terms of rate of chemical deterioration. This is due to winter closing of properties resulting in low average annual temperatures. This damage function will be useful in comparing rates of chemical deterioration before and after making alterations to the environment of an object to ensure there are no unexpected consequences from moving an object or changing the heating regime, for instance.

Conclusions

The historical building simulation has shown the range of RH conditions that might have been experienced by collections in a historic house in England. Until the late nineteenth century, the characteristic conditions in unheated or lightly heated buildings would have been rather high RH, as is still apparent at Knole. In the late nineteenth century and early twentieth century, the introduction of central heating systems to buildings with high heat loss probably caused a modest reduction in room RH, which would have been largely beneficial. However, if heating systems were operated at maximum output, rooms with sufficient heating surface installed could experience low winter RH, leading to damage to vulnerable materials such as decorated furniture, panelling and paintings. As the twentieth century progressed, heating systems became more powerful and the potential for damage from low RH increased [13].

The climate risk assessment tools developed for mould growth prediction demonstrated good correlation between prediction and observation for the limited data set investigated. The tool was better than the current National Trust RH metric because it combines the pattern of RH and temperature over time rather than simply calculating how often RH exceeds desired thresholds. Three of the main factors required for mould growth (RH, T and time) are considered rather than RH alone.

The lack of correlation between the observed mechanical damage and prediction requires further investigation, particularly of the response of complex objects. As condition reporting has evolved over the past 50 years, a form of condition assessment more specifically designed to reveal correlations between object response and environment is needed, as well as a larger dataset. Further development of the damage function may be helpful to account for the innate fragility of objects according to their methods and materials of construction, the impact of the historic environment and effects of high RH on adhesives.

Nonetheless, both mould and mechanical damage functions demonstrated the collections at Ightham Mote were at a lesser risk than at Knole, a finding that correlates well with condition surveys. The current National Trust metric might lead someone unfamiliar with the properties to see Ightham Mote as having almost as poor an environment as Knole.

The National Trust has generally considered its collections to be at greater risk from biological and mechanical deterioration than chemical deterioration, which is borne out by our chemical deterioration rates being lower than in an 'ideal' museum due to low average temperatures, also beneficial for saving energy (and money).

In the near future we hope to continue our investigations into the application of climate risk analysis to build confidence in assessments and to trial their application more widely with National Trust conservators and property staff. Work is also ongoing to investigate the energy consumption of conservation heating systems and ways to increase efficiency whilst still maintaining good conditions for collections. Climate risk analysis has the potential to support this work through the prediction of 'safe' and 'unsafe' climate regimes.

References

[1] Staniforth, S., Hayes, R., and Bullock, L., 'Appropriate technologies for relative humidity control for museums housed in historic buildings', in: Preventive Conservation, Practice, Theory and Research, Preprints of the Ottawa Congress, 12-16 October 1994, eds. P. Smith, A. Roy, IIC, London (1994) 123–128.

[2] Staniforth, S., Blades, N., and Lithgow, K., Specification for Environmental Control, National Trust Guidance Note, National Trust (2010) (unpublished).

[3] Sedlbauer, K., Prediction of mould fungus formation on the surface of and inside building components, Fraunhofer Institute for Building Physics, Holzkirchen (2002).

[4] UK National Museum Directors Council, Guiding principles for reducing museums' carbon footprint, http://www.nationalmuseums.org.uk/media/documents/what_we_do_documents/guiding_principles_reducing_carbon_footprint.pdf (accessed 20 August 2012).

[5] Ferris, F., (ed.), 'Buildings discovered which still have items of interesting historical engineering equipment heating National Trust properties' http://www.hevac-heritage.org/items_of_interest/items_of_interest.htm (accessed 16 August 2012).

[6] Hood, C., A practical treatise upon warming buildings by hot water and upon heat and heating appliances in general, rewritten by F. Dye, 3rd edn., E. & F.N. Spon, London (1897).

[7] Taylor, J., Blades, N., Cassar, M., and Ridley, I., 'Reviewing past environments in a historic house library using building simulation', in ICOM Committee for Conservation, 14th Triennial Meeting Preprints, ed. I. Verger, James & James, London (2005) Vol. II 708–715.

[8] Jones, W., Heating by Hot Water, 2nd edn., Crosby, Lockwood & Son, London (1894).

[9] Martens, M., Climate Risk Assessment in Museums - degradation risks determined from temperature and relative humidity data, PhD Dissertation, University of Technology Eindhoven (2012) (unpublished). Climate risk assessment tool can be accessed from: http://www.monumenten.bwk.tue.nl/Default.aspx (accessed 24 August 2012).

[10] Bratasz, Ł., Kozłowski, R., Kozłowskaa, A., and Rivers, S., 'Conservation of the Mazarin Chest: structural response of Japanese lacquer to variations in relative humidity', in ICOM Committee for Conservation, 15th Triennial Conference Preprints, ed. J. Bridgland, Allied Publishers, New Delhi (2008) Vol II 1086–1093.

[11] British Standards Institute. 'PAS 198:2012 Specification for managing environmental conditions for cultural collections.' http://standards-online.co.uk (accessed 1 May 2012).

[12] ASHRAE, 'Museums, Galleries, Archives and Libraries', in ASHRAE Handbook – HVAC Applications, American Society of Heating, Refrigeration and Air Conditioning Engineers (2011) 23.1–23.22.

[13] Staniforth, S., 'Relative humidity as an agent of deterioration', in National Trust Manual of Housekeeping, National Trust, Swindon (2011) 102–113.

Authors

Nigel Blades is Preventive Conservation Adviser (Environment) at the National Trust where he advises on environmental control for the care of collections including reservicing of historic house heating systems for delivery of conservation heating. Email address: nigel.blades@nationaltrust.org.uk

Katy Lithgow is Head Conservator at the National Trust, with particular interests in preventive conservation, wall painting conservation and conservation management for public benefit, and serves as chair for ICON's professional accredited conservator-restorer scheme. Email address: katy.lithgow@nationaltrust.org.uk

Hazel Jessep is student at University College London Centre for Sustainable Heritage, currently completing an MSc in Sustainable Heritage. She is a qualified Architect. Email address: hazel.jessep.11@ucl.ac.uk

Image credits

Figure 1 (large). © National Trust Images/ Rupert Truman
Figure 6. © National Trust Images/ Andreas von Einsiedel

Licence

A museum storage facility controlled by solar energy

**Morten Ryhl-Svendsen, Lars Aasbjerg Jensen,
Poul Klenz Larsen, Benny Bøhm and Tim Padfield**

Abstract

We describe a museum storage building which controls its climate by solar heating. The temperature is moderated by heat storage in the ground below the floor while a highly insulated superstructure and good airtightness shield against variation in weather. The relative humidity is kept moderate by solar heating of the attic space through a roof window. The heat is slowly released through the ceiling to the storage space below. This will give a temperature which cycles annually between 10 °C and 25 °C. Fine humidity control can be achieved by use of moisture reactive wall surfaces, such as clay in the form of unfired brick.

Introduction

Museums are emerging from a long period when climate control by the best available technology was accepted as the only ethical way to run a museum. Rising fuel prices and predictions of dire consequences from carbon dioxide emission from fossil fuel burning have forced a reappraisal of this comfortable model of the ideal museum. Energy saving is most easily achieved in museum stores and archives. This has led to the building of low-energy stores with surprisingly gentle climatic variation achieved by simple means. Stores without active temperature control have been built with mechanical dehumidification as the only active climate control device. We explore here the merits and disadvantages of a museum storage building which controls its climate by solar heating, without any active intervention at all – a store that requires no electricity and no sensors for its climate control.

The operating principle of the passive store

1. The temperature cycle through the year is moderated by massive buffering by the floor, which is laid on the ground without insulation. This means that the floor area must be large and the store must be single-storey, though perforated mezzanine platforms are permissible.
2. The influence of day-to-day weather is minimised by an airtight, well-insulated building envelope above ground. This may be lightweight, since thermal inertia is provided by the ground and to some extent by the collection objects.
3. The relative humidity (RH) is buffered by extensive use of moisture-reactive wall surfaces, for example, unfired brick used as a veneer or as a wall construction material.
4. The tendency towards high relative humidity is compensated by solar heating of the attic space, with slow release of heat through a massive ceiling. Solar heating is greatest during the summer, so both humidity and temperature buffering are essential to avoid a damaging high summer temperature.

The low-energy storage building

Some of these characteristics are already present in museum stores; some have been explored in small experimental constructions and some are only computer-generated predictions. In this article we base our argument on an existing storage building in Ribe in south west Denmark (Figure 1), extending its measured performance by computer simulation to move a step further towards low-energy, fully passive climate control.

Temperature control

In Denmark a well-insulated but lightweight single storey building with an un-insulated, typically concrete, floor laid directly on the ground will provide an annual temperature cycle between about 7 °C and 15 °C, averaging 12 °C (Figure 2). The building envelope shields against the rapid changes in weather, while the ground below the floor acts as a heat store, which allows the indoor air temperature to follow the annual temperature cycle outdoors with reduced amplitude.

Humidity control by mechanical dehumidification

The relatively low temperature indoors in summer will result in an excessively high RH, so mechanical dehumidification is used in the Ribe building. Due to a very low air exchange rate (less than 1.0 per day), which minimises the infiltration of excess moisture, a stable RH at 50 % can be maintained throughout the year for about 2 kWh per cubic metre of storage space. This is the measured energy consumption of the Ribe store [1,2]. A benefit of the low air exchange rate is that the infiltration of pollutants is very slow. However, internally-generated pollutants may then accumulate but can be removed by recirculating air through a sorbent filter, or by passive sorption on a reactive wall material [2 to 5].

Up to three-quarters of the energy consumed is used by the dehumidification process and the rest is used by the air recirculation fans. In the 6500 m^3 storage building in Ribe, a 2 kW absorption dehumidifier runs almost constantly from July to September. However, during the winter it is inactive for weeks at a time. The building is currently connected to the energy grid, but it

Figure 1. The storage building for the Museums of south west Denmark, in Ribe. Architect: Bo Christensen ApS, Engineers: Birch and Krogboe A/S. Opened in 2005
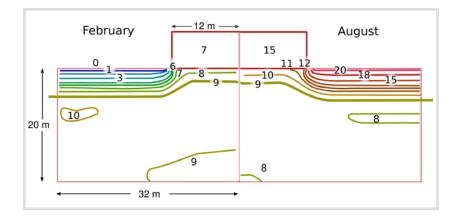
Figure 2. Cross section showing temperature buffering by the ground beneath a large building, 24 metres wide and very long. The store has well insulated roof and walls but the concrete floor is un-insulated. On the left is the Danish winter situation with an inside temperature of 7 °C in February. To the right is the summer situation with 15 °C indoors in August. The ground acts as a heat source in winter and as a heat absorber in summer. As years go by, the ground under the building approaches the annual average temperature within the building, regardless of the natural climate outside. Technical details of the computer simulation are given in the appendix

is tempting to imagine a set-up in which the building can be energy independent and operate totally off-grid.

Energy from solar panels

At present, mains electricity is used for dehumidification. The consumption is mainly during the summer, so solar energy is an obvious source. Figure 3 shows the energy used for air conditioning in the Ribe building, based on measurements from 2009 to 2010.

The figure also shows a prediction of the energy which would be provided by a solar panel of 12 % conversion efficiency covering 5 % of the roof area (60 m^2) and tilted to the south. Such an arrangement would on average provide the right amount of energy. However, there will be times when the panels produce more energy than needed (spring-summer), and other times where the production is too small to cover the fan energy, though it is always sufficient to drive the dehumidifier.

A backup connection to the main energy grid may still be advantageous, so electricity shortage or surplus can be traded in and out of the building. Recirculation for pollutant control can be intermittent, increasing when the sun shines.

Dehumidification compared with conservation heating

Dehumidification without moving parts is difficult but would provide a superior environment because the summer temperature is kept low, with consequent slowing of deterioration reactions. Typically the rate of deterioration will be about halved in a cool storage building as compared to an exhibition gallery heated for people's comfort. However, while this is a relevant issue particularly for modern collections, other collections of more robust objects will tolerate a higher storage temperature, even for long-term storage. If one aims at a totally passive solution, without moving parts

and control electronics, an alternative is to heat the building to achieve a moderate RH. This process of controlling heating to maintain a constant RH rather than a constant temperature is called conservation heating. One way to achieve this is by direct solar heating, most conveniently provided by heating an attic above the storage room through a window in the roof. Heat then diffuses down into the storage room through a concrete ceiling.
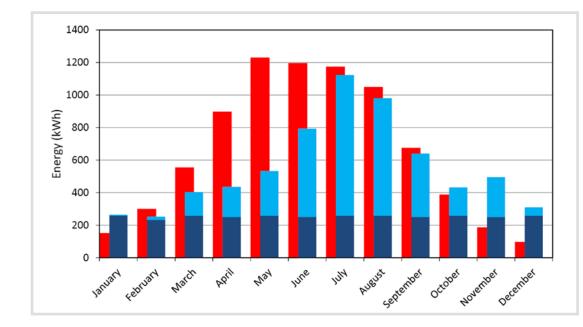
The construction is sketched in figure 4. The thermal mass of the ceiling will minimise the daily temperature variations, while the thermal mass of the floor will reduce the annual variation. This, in combination with a low air exchange rate and humidity buffering (discussed below), will give an annual cycle of room climate with a moderate RH but with a higher summer temperature than in a dehumidified and unheated building.

Dehumidification by solar heating

To our knowledge, no museum store exists today with humidity control by solar heating. However, by computer simulation we demonstrate how a building similar to that in Ribe could be designed to maintain an annual RH variation held within the band 40 % to 60 % by heat gain through a roof window. The annual temperature profile is then predicted to cycle between 10 °C and 25 °C. A south facing window covering 7 % of the roof area (80 m^2) will achieve that (Figure 5).

Relative humidity buffering as a supplement to conservation heating

The relatively high temperature required to keep the RH down in summer accelerates degradation reactions. The temperature excess over ambient in summer can be minimised by relying on RH buffering to tide the store over the summer temperature theoretically required to keep the RH moderate. The store will be out of equilibrium with the water content of the outside air but will be buffered by the unfired clay wall cladding. In winter, the humidity buffering operates to increase the low RH which would theoretically result from the floor heating.
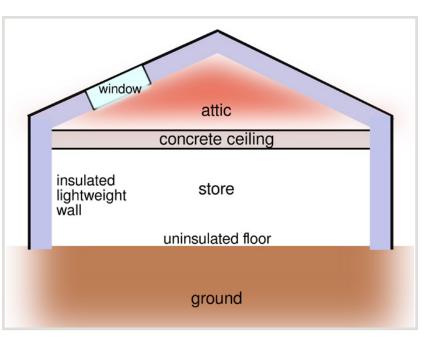
Figure 3. The monthly energy used for air conditioning in Ribe (measured in 2009 to 2010), compared with the predicted energy provided by a solar panel (12 % efficiency) covering 5 % of the roof area and facing south. Light blue: dehumidifier (measured). Dark blue: fan (measured). Red: Solar panel (measured)

Evidence for the effectiveness of humidity buffering in museum stores has been presented in several publications [3, 6 to 8]. Padfield and Jensen [9] have quantified the buffer performance of various materials and have proposed a method for predicting the buffer performance of buildings. Their analytical method has been applied to an experimental buffered room, without stored materials, to demonstrate the effectiveness of buffering even in stores without moisture-reactive artifacts.

The room has concrete walls, gypsum plastered and painted. It has two outer walls with a west-facing window. The volume is 26 m^3 and the surface area of wall is 56 m^2. Only 7.5 m^2 of an internal corner of this wall is covered with unfired brick, 110 mm thick. The measured air exchange rate is 0.125 per hour.

In figure 6 the predicted course of the RH is derived from the B-value for unfired clay brick as defined and measured by Padfield and Jensen [9]. Briefly, the B-value is the volume in cubic metres of air whose RH will change equally to the change in equilibrium RH at the surface of a square metre of the material when the same amount of water vapour is added to the air as to the material. This apparently complicated definition of buffer capacity allows a simple approximate calculation of the stabilising effect of various wall covering materials, as well as of stored materials.

The smoothness of the predicted RH is due to using the long term B-value appropriate to a nearly airtight enclosure. Over shorter periods of fluctuation the B-value is smaller, because only the surface layer of the buffer is involved. In this particular room the absorbent walls do not calm the daily spikes in RH caused by sunlight, because the temperature of the wall surface is also buffered and is therefore more constant than the air temperature where the RH is measured in the centre of the room.

The stability of this empty room, imposed by a relatively small portion of the wall surface, shows that humidity buffering will greatly reduce the effect of variation in solar gain with changing weather.

Figure 5. The indoor climate inside a store with a roof window. The RH is kept within 40 % to 60 % at all times. The RH is moderated not only by solar heating but by buffering by a lining of unfired clay brick. This computer simulation is based on the Ribe storage building and the Danish Reference Year for weather (details in the appendix)
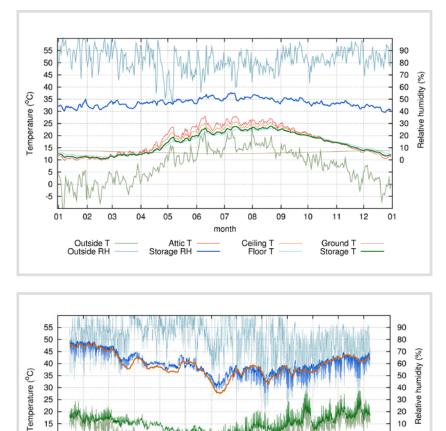
Figure 6. The measured course of the climate within a room partly lined with clay bricks. The smoother, orange trace is the RH predicted for the room, assuming a B-value 100 for the unfired clay brick. See Padfield and Jensen [9] for an explanation of the calculation

The simulation of the large store shown in figure 5 also includes humidity buffering, but through a more elaborate calculation.

Besides the excellent moisture-buffering capacity of clay, the material has a great potential for absorbing reactive compounds from the air, especially acid gases, and therefore acts as a pollution sink [5], compensating for the lack of air circulation machinery in a totally passive store.

Conclusion

We have shown, through a combination of climate-predicting simulation and experience from actual buildings, that museum stores can be air conditioned completely passively, if a period of relatively high summer temperature is acceptable, or with only locally collected solar energy used to supply a mechanical dehumidifier if there is a need to keep the temperature low. In both models it is essential to keep the air exchange rate low and it is essential to use the earth under the building as a heat sink. Pollution from outside air is excluded; pollutants generated within the building can be absorbed from recirculated air, if electrical power is available; for a truly passive store one must rely on a reactive wall lining.

References

[1] Ryhl-Svendsen, M., Jensen, L.A., Larsen, P.K., and Padfield, T., 'Does a standard temperature need to be constant?' Meddelelser om Konservering 1/2010 (2010) 13–20, www.conservationphysics.org/standards/standardtemperature.php

[2] Ryhl-Svendsen, M., Jensen, L.A., Larsen, P.K., Bøhm, B., and Padfield, T., 'Ultra-low-energy museum storage', in ICOM-CC 16th Triennial Conference Preprints, Lisbon, Portugal, 19–23 September 2011, ed. J. Bridgland, International Council of Museums – Committee for Conservation, London (2011), http://www.conservationphysics.org/ppubs/ryhl-svendsen_low_energy_store_icom-cc2011.pdf (accessed 19 April 2013)

[3] Padfield, T., Larsen, P.K., Jensen, L.A., and Ryhl-Svendsen, M., 'The potential and limits for passive air conditioning of museums, stores and archives', in Museum Microclimates, Contributions to the Copenhagen Conference, 19–23 November 2007, ed. T. Padfield, K. Borchersen, National Museum of Denmark, Copenhagen (2007) 191–198, www.conservationphysics.org/musmic/musmicbuf.pdf

[4] Ryhl-Svendsen, M., and Clausen, G., 'The effect of ventilation, filtration and passive sorption on indoor air quality in museum storage rooms', Studies in Conservation 54 (2009) 45–48.

[5] Ryhl-Svendsen, M., 'Passive sorption of organic compounds on clay bricks', in INDOOR AIR 2011, the 12th International Conference on Indoor Air Quality and Climate, Austin, Texas, 2011, ed. R. Corsi and G. Morrison, International Society of Indoor Air Quality and Climate, Santa Cruz, California (2011).

[6] Padfield, T., and Larsen, P.K., 'Designing museums with a naturally stable climate', Studies in Conservation 49 (2004) 131–137, www.conservationphysics.org/musdes/musdes.pdf

[7] Padfield, T., and Larsen, P.K., 'Low-energy air conditioning of archives', in the ICOM-CC 14th Triennial Meeting, The Hague, 12–16 September 2005, ed. I. Verger, James & James, London (2005) 677–680, www.conservationphysics.org/arnemag/arnemag_nrwch.pdf

[8] Larsen, P.K., Ryhl-Svendsen, M., Jensen, L.A., Bøhm, B., and Padfield, T., 'Konstantes Raumklima und niedriger Energieverbrauch – kein Widerspruch', Restauro 7 (2012) 53–60.

[9] Padfield, T., and Jensen, L.A., 'Humidity buffering by absorbent materials', in NBP 2011 – 9th Nordic Symposium on Building Physics, Tampere, Finland, Vol. 1 (2011) 475–482. An extended version of this article is at: http://www.conservationphysics.org/ppubs/humidity_buffering_building_interiors_nsb2011.pdf (accessed 19 April 2013)

Appendix
Technical details of the simulations

Solar heating was simulated for a building similar in construction to that of the storage building for the Museums of south west Denmark, in Ribe. The simulation software was BSim, version 6,11,1,14, by the Danish Building Research Institute (SBI) at Aalborg University, http://www.bsim.dk. For outdoor climate, the Danish Reference Year was applied to the model, and the building was given the same geographical orientation as the real building. The gables were facing east-west. The roof had a 20°pitch. Solar panels or window were tilted towards the south.
Internal dimensions of the storage room: 41.73 m x 24.73 m x 6.48 m high.

Model construction:

Walls (from the inside): Unfired clay brick 110 mm; PVC vapour barrier 0.2 mm; Mineral wool thermal insulation 250 mm; Board 26 mm. Total thickness 386 mm. U-value 0.13 W/m^2K. Ceiling: Concrete 100 mm. U-value 2.5 W/m^2K. Floor: Concrete 200 mm laid directly on the ground; Soil 7800 mm. Total thickness of the ground element: 8000 mm. U-value (concrete floor) 1.3 W/m^2K. U-value (concrete and soil element) 0.25 W/m^2K. Window: 80 m^2: Low-energy type glass in aluminium frame. U-value 0.56 W/m^2K. Air exchange rate: 0.03 $hour^{-1}$. The real building in Ribe has an inside lining of fired Moclay brick instead of unfired brick.

The temperature gradients shown in figure 2 are based on a heat transfer simulation by computer, using the Danish Reference Year for outdoor conditions. The simulation was made with Comsol Multiphysics (version 3.5a), using the same construction as the actual building in Ribe. In the real building in Ribe temperatures have been monitored inside and outside since 2008, both in the air and underground to a depth of 2 metres. These data were published by Ryhl-Svendsen et al. [2]. The measurements show a higher indoor air temperature in winter than is predicted by the model (about 9 °C), and also the measured soil temperature at 2 metres was higher (about 12 °C). These elevated temperatures are due to unintended heating of the storage room by the fan, dehumidifier and lighting. Besides this there may be a variation in climatic influence from year to year, which differs from that of the standardised (artificial) reference year.

Authors

Morten Ryhl-Svendsen is a senior scientist at the National Museum of Denmark. Email: morten.ryhl-svendsen@natmus.dk (author for correspondence).

Lars Aasbjerg Jensen is a conservator at the National Museum of Denmark. Email: lars.aasbjerg.jensen@natmus.dk.

Poul Klenz Larsen is a senior consultant at the National Museum of Denmark. Email: poul.klenz.larsen@natmus.dk

Benny Bøhm (retired 2011) was a climate consultant with the National Museum of Denmark

Tim Padfield was formerly with the National Museum of Denmark. He is now a freelance consultant in preventive conservation, based in Devon UK. Email: tim@padfield.dk

Passively conditioned zero-energy storage for cultural properties and archival material

Lars Klemm

Abstract

Many types of archival material and cultural heritage objects can only be preserved in an adequate store or archive. Most museums continue to collect but the space to store growing collections is rarely expanded, and in many cases it may even be reduced in favour of additional exhibition space. Archives face a comparable situation. Every archive has the duty to conserve historical documents, which results in hundreds of kilometres of new archival documents every year to be stored and preserved. The probability that during an archivist's lifetime a new archive building will be built or the existing one will have to be extended is about 100 %.

Museums designed in the last 40 years are characterised by a series of specific functions. However, as all architectural typologies are subject to a process of change and modernisation, museums have also evolved over time to become more complex. Museums have changed from spaces of permanent exhibition, storage and conservation to public places with various functions including permanent and temporary exhibitions, study and science, storage and conservation, restaurants, commercial and education facilities and other multi-use activities. During this development, provision of sufficient storage space for collections has occasionally been overlooked.

Few museums are able to store their entire collections permanently inside their main buildings. Large parts of museum or archive collections may be located in off-site storage, where they can be exposed to significant risks of damage. Although storage is at the heart of a museum's function, in some cases surprisingly little attention is paid to providing adequate storage conditions. International standards prescribe tight climate control values, which lead to energy- and cost- consuming air-conditioning systems. However, these systems do not achieve the desired results for collections nor are they affordable in the long term. Even in times of reduced cultural budgets and rising energy prices many museums and archives pour resources into unique and expensive buildings designed to meet those climate requirements and satisfy design aesthetics. Extensive heating, ventilation and air-conditioning systems are installed to achieve stable environments and the high energy and maintenance costs are accepted.

This situation was the starting point for a study in 2011 at the Fraunhofer-Institute for Building Physics (IBP). Its main focus was on passively conditioned zero-energy storage and archive buildings. The objective was to develop an economical and sustainable solution for a zero-energy building, which achieved conservation requirements, neutral energy balance and modular design. The Fraunhofer-Institute designed a new zero-energy storage system with the following research objectives:

1. Easy and economical storage and archive solutions
2. Sustainable planning
3. Multipliable concepts by modular components
4. Cost-efficiency by applying prefabricated construction elements
5. Providing market-ready energy-efficient concepts.

Museums and archives are repositories of knowledge for a modern society; therefore, energy-efficient solutions for these buildings are necessary to maintain valued collections over generations. The results of the study demonstrate that zero-energy storage systems are possible and that technical solutions are partially ready for the market.

Study for the development and examination of a modular zero-energy storage

Modern storage and archive buildings are often very expensive: the building costs are high and the technical equipment causes unreasonably high running costs. Overall the price for a storage or archive building is about 1850 € to 2000 € per square meter. Only very few outstanding projects cross this price threshold, such as the Danish storage buildings in Vejle and Randers, the KHM store in Vienna or the new store in Freiburg/Breisgau. In a context of rising energy prices and reduced cultural budgets it is vital to find solutions for new, economic and effective storage and archive buildings.

One of the current tasks of preventive conservation is to find sustainable storage and archive solutions. That means buildings must save energy and have low maintenance costs as well as achieve conservation standards. It seems quite evident that the only way to achieve low-priced storage buildings will be to use modern industrial architecture. With a modern industrial construction concept it is possible to build a low-cost framed hall within four to six months. The challenge is to transform this building concept into an adequate standard for a store that accords with preventive conservation principles and, if possible, to optimise this concept by modular construction methods which would be suitable for most locations.

This was the aim of the study at the Fraunhofer IBP in cooperation with Südhausbau and k3-artservives. The first step was to develop the concept of different module types for storage and archive building, such as a painting module, an archaeological collection module, a furniture module, an archive module etc. The next step was to simulate a virtual model of the prototype of a modular store to examine the indoor climate conditions and the zero-energy concepts. Finally, it was intended to build the first modular store as an example of best practice. First it was necessary to define the preventive conservation parameters for a modular prototype storage building, particularly in terms of optimal room size, storage management and collection handling, functional architecture, fire protection, safety, pest management, indoor climate (including air exchange rate and wall thickness), heat transfer coefficients of walls, floor and roof and so on. It is important to refer to industrial standards (e.g., on the size of the prefabricated wall and roof elements, which define the raster, size and volume, of the storage and functional module, the shelving system, doors and gates etc.) when determining the parameters for the modular and passively conditioned concept. This is the

reason why the study set its focus on prefabricated concrete double wall elements with core insulation. The aim was to develop a low price modular store type (about 1000 € per square metre including shelving system, a price achieved at the KHM store in Vienna), that complied with nearly all aspects of preventive conservation and operated as a zero-energy building. It was necessary to subordinate all other aspects to this overall goal.

A simple, safe construction approach for a conservation store requires basic, low-maintenance and energy-efficient installation engineering. Floor heating combined with ventilation is therefore the best solution. If possible a humidification and dehumidification system should be avoided. Furthermore, the building should successfully operate without cooling, even if the predefined climate limits are moderately exceeded during some days a year. The energy consumption of the storage building should be as low as possible and at the same level as the regenerative energy gain of the building. Taking into account their aspects of maintenance and use, stores or archives are the perfect building class for a passively-conditioned concept and a zero- or even plus-energy building. However, it is ineffective to achieve this standard by expensive construction materials and planning costs. The quality must be realised with a simple and low-cost construction method. For that reason all building components had to be produced by fast and efficient industrial processes. The fire prevention for the modular concept is also simple; no fire extinguishing system is required. Preventive fire precautions are strictly implemented: each module is a separate fire compartment equipped with a carbon monoxide early-detection sensor. The security and fire alarm system must be arranged at the specific location and with the input of the local emergency services.

To achieve space optimisation and to take full advantage of industrial efficiency each module can only be obtained in two room heights, 350 cm and 700 cm, and the width of walls is limited to a raster of 275 cm. This permits the application of standard shelves and mezzanine systems and limits production, transport and construction costs. It is not the aim to achieve an individual solution for each collection in the museum but rather an all-round solution that fits for a large part of every collection. The modular concept offers the possibility of future extension of the store or archive building if necessary and as far as the building site permits. For this reason, all storage and archive modules must be standardised: any extension or enlargement can be achieved simply by adding another module, no rearrangement of the collection would be necessary for future development.

This approach offers the potential for sustainability in terms of both economic and energy resources and the prefabricated modules are suited to the specific needs of museums and archives. When museum professionals or archivists start to think about new storage and archive buildings, one of the first issues to be addressed is the climate conditions required. For optimal preservation of the stored artworks, storage buildings and archives require stable interior climate conditions, with minimal and slow variations in temperature and relative humidity. Stable climate values are important but there are also other significant risks to be considered seriously: fire, theft, high-operating expenses and the overall costs of the building during its full life cycle. However, for the study the interior climate conditions were balanced with

Table 1. Environmental conditions for the archive and painting modules

Module Type	Temperature [°C]	Relative Humidity [%]
Archive Module (DIN ISO 11799)	14 – 18 plus or minus 1	35 – 50 plus or minus 3
Painting Store	16 – 22 plus or minus 2	40 – 55 plus or minus 5

economic efficiency and low energy consumption. The aim was to create a suitable overall climate for 95 % of the collection, while special solutions had to be found for the remaining 5 %. The German Standard DIN ISO 11799 describes the requirements for the environmental conditions of archive collections. These climate limits are similar to the current version of the British standard PAS BSI 198:2011 Specification for environmental conditions for cultural collections. Other comparable regulations do not exist in Germany. Within the study two modules with different indoor climate conditions were tested: an archive module mainly for paper and a storage module for paintings. To define the climate range for the painting store the loan contracts of several German museums were adapted. Table 1 shows the condition range for the archive module and for the painting storage module.

To examine a variety of construction materials and for the assessment of construction strategies for both module versions (the archive indoor climate and the painting storage indoor climate) the prototype architecture was built up in a hygrothermal building simulation programme (WUFI-Plus®). The prototype store is a basic building within two modules, a functional module with delivery, workshops and engineering room and a storage module (Figure 1). The simulation results supported the decisions
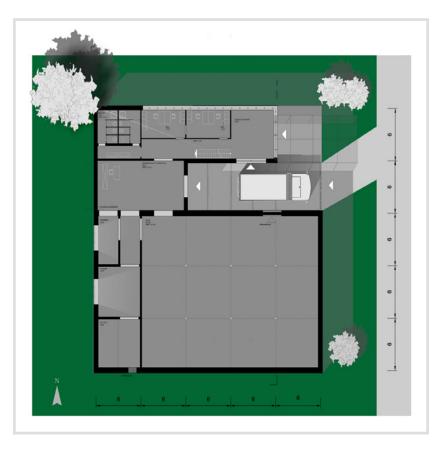
Figure 1. Prototype of a modular storage building

about which type of wall insulation, which air exchange rate and other conditions met the requirements of a modular passively conditioned zero-energy storage and archive building. Calculations of the building's energy modelling based on the German Standard DIN V 18599 (Energy Efficiency of Buildings) where used as the basis for the evaluation of optimisation measures. The primary aims of these optimisation measures were:

- reducing the humidification, dehumidification, conservation heating and cooling necessary to achieve a passively-conditioned climate instead of active conditioning with heating, ventilation and air-conditioning (HVAC) systems;
- optimisation of prefabricated construction elements and the effects of additional insulation of walls, roof and floors;
- examining the impact of user behaviour on air exchange rates;
- achieving long-term indoor climate stability to protect the objects;
- the use of thermal and hygric buffer materials for both types of storage modules;
- maximum airtightness for the building allowing a minimum energy supply.

Hygrothermal building simulation

The WUFI-Plus® software was used for the hygrothermal building simulation to examine the annual climate conditions in the store and to examine the influence of construction and insulation materials. The calculations were performed for the storage room rather than for the whole building. Table 1 shows the environmental conditions for temperature and relative humidity for the archive and for the painting module. The hygrothermal calculations for both types assume an operating time of five years and the representative outdoor climate conditions of Würzburg. The long-term behaviour is assessed by the evaluation of the fifth year to guarantee exact results. The influence of the construction moisture in a nearly air-tight store is demonstrated by evaluating the first year's simulation results. The simulation includes the outside conditions, the building envelope (walls, roof and ground

Table 2. Specifications for the three variations
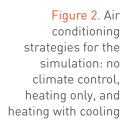
Variation	Basic variation	Optimised variation	Foam glass variation
Floor	10 cm XPS 30 cm Concrete Bitumen lane 6 cm Parquet U-Value: 0.276 W/m²K	20 cm Foam glass 30 cm Concrete Bitumen lane 6 cm hardwood construction U-Value: 0.177 W/m²K	As basic variation
Outer Wall	6 cm Concrete 14 cm EPS 18 cm Concrete U-Value: 0.214 W/m²K	6 cm Concrete 14 cm Phenol resin foam 10 cm Concrete U-Value: 0.151 W/m²K	28 cm foam glass panels U-Value: 0.132 W/m²K
Roof	Roofing membrane 16 cm mineral foam sheets 25 cm porous concrete U-Value: 0.153 W/m²K	Roofing membrane 16 cm Phenol resin foam U-Value: 0.098 W/ m²K	As basic variation
Inner Wall	10 cm Phenol resin foam 13 cm Concrete U-Value: 0.274 W/m²K	As basic variation	As basic variation
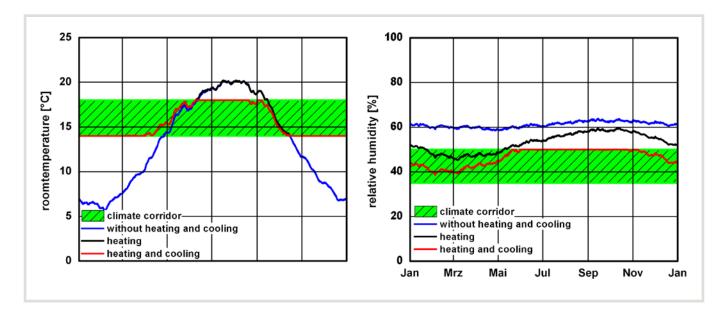
floor), the conditions for heating and cooling, indoor climate, air exchange rates, lighting and CO_2). The specific material parameters are provided from the WUFI®-Plus database or were determined experimentally (canvas, wooden painting frames, paper archive material and metal shelves). The conditions for the ground are defined as 9 °C plus or minus 4 °C, and 100 % RH; for the delivery zone as 18 °C plus or minus 9 °C, and 60 % RH plus or minus 10 %; and for the workshop as 18 °C and 50 % RH plus or minus 5 %. The simulation was based on three variations, two of different prefabricated double wall structures with core insulation: one with polystyrene foam insulation, which was the basic option, and the other with phenol resins foam insulation, the optimised option. A third variety of wall consisted only of foam glass so a type of construction without the negative effects of construction moisture could be evaluated.

The basic variation reveals thermal and hygric behaviour as presented in the graphics of figure 2. In the simulation the following climatisation strategies were varied:

1. No climate control
2. Heating only
3. Heating with cooling to achieve the climate marked in green.

With no climate control in the archive storage the temperature in winter would drop to 5 °C and in summer exceed 20 °C, so the target of a maximum of 18 °C could not be met. To achieve the strict conditions of the climate limits for the archive storage (as fixed in DIN ISO 11799) heating and cooling would be necessary. Furthermore, the relative humidity in the storage is not acceptable without climate control. With a level of about 60 %, the relative humidity would be permanently too high. If the archive was heated in the winter, the limit of 14 °C could be achieved and the relative humidity could be reduced at least in the first four months of the year. In the summer, the same temperature curve arises and the relative humidity would be slightly over the limit. Only control of both heating and humidity would guarantee conditions within the required climate corridor. If the store were only heated, the daily fluctuations of temperature would be 0.3 K and 0.9 % RH. The acceptable maximum of daily fluctuations is 1 K and 3 % RH,

Figure 2. Air conditioning strategies for the simulation: no climate control, heating only, and heating with cooling

which could be achieved with the heating strategy combined with the basic construction design option. With a wider climate range the situation for the painting storage is more favourable. With no climate control, there would be a similar environment to that of the archive module in terms of ambient temperature. Indeed, the established maximum temperature would not be exceeded so cooling would not be necessary. However, over the annual and daily time-frames the relative humidity shows higher fluctuations. This is due to the weaker humidity-buffering capacities of a painting collection when compared to a paper archive of the same size. For a painting storage unit daily fluctuations of 3 K and 5 % RH (average value based on different loan contracts) are allowed. With heating, maximum daily fluctuations of 0.4 K and 1.1 % RH can be achieved with the basic construction design option.
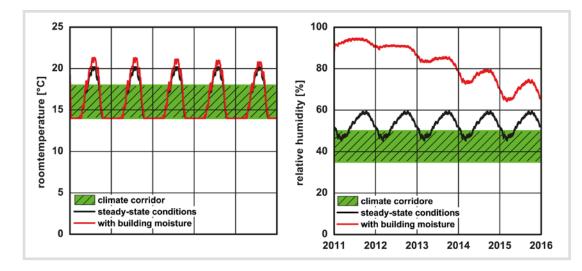
Conclusion of the building simulation

The results of the simulation demonstrated that the basic and the optimised options would be more suited for painting stores (or other collections with the same climatic limits). The indoor climate range of 6 K and 15 % RH has a bigger potential for a passive conditioned status. Cooling is not necessary with a maximum temperature of 22 °C; heating would ensure the RH remains within the specified range (though there would be some occasions in spring when the RH would be too low, and some days autumn when the humidity would be too high).

Should these conditions be considered satisfactory it is possible to achieve a very good conservation store by using the optimised construction option, which has a minimal energy requirement (except for during the first operational years when the moisture in the construction materials would need to be dried out). However, the more rigid conditions for the archival material would require HVAC in the archive module, with concurrent higher energy consumption for heating and cooling. The prescribed climate conditions for both collections can be achieved with the optimised module option. In the case of the archive module, heating and cooling would be necessary, but the daily fluctuations are limited to 0.3 K and 0.9 % RH (with the heating only strategy) as an effect of the massive hygric buffer of the archive papers. Without this buffer, the daily fluctuation for the painting module (with a lower hygric mass of wood and canvas) is 0.4 K and 1.1 % RH with the same strategy of climate control (heating only).

All variations of environmental control and building option were compared. All variations for the archive module achieved low daily fluctuations of 0.3 K and 0.9 % RH. The maximum daily fluctuations in the painting storage were 0.4 K and 1.1 % RH for the basic and optimised building options, and 0.8 K and 1.2 % RH for the foam glass variation.

Furthermore, the influences of the construction moisture, the air exchange rate, the archive material (amount of paper) and the floor plate were examined for the archive module because of their likely hygrothermic impact. The construction moisture and its influence in the basic building option are shown in figure 3. It appears that the existing high construction moisture in the prefabricated concrete double wall (with or without core insulation) causes high moisture content in the store. Due to the low air exchange rate of 0.05 per hour, this influence was reduced very slowly and would

Figure 3. Influence of concrete construction moisture on the low air exchange rate module

continue to affect the store even after five years. Because concrete dehumidifies slowly, a very long drying period would be necessary before the store would be ready for the installation of collections.

Figure 4 shows that an increase of the air exchange rate causes lower summer temperatures and lower relative humidities in winter. With an air exchange rate of 0.2 per hour the maximum daily fluctuation is still within the limit values, but clearly higher than with an air exchange rate of 0.05 per hour. When increased to 0.5 per hour, the daily fluctuations are considerable, at 5.7 K and 5.5 % RH, thus clearly out of the acceptable range. The size of the archive collection in the store has a marked impact on the indoor climate. The summer temperatures are similar with a full or a half-filled archive module, but when empty there are noticeably higher temperatures. In terms of relative humidity, there is also only a small difference between a full and half-filled store though the short-term fluctuations are higher when the archive is half filled. Without any archive material at all the annual fluctuations in relative humidity are much more severe, ranging between approximately 38 % and 64 % RH. The size of the archive collection also has a big influence on daily relative humidity fluctuations: the maximum daily fluctuation is 4.1 % RH in an empty archive, which exceeds the acceptable values. The influence of the insulation of the ground floor is also significant. The absence of floor insulation (as observed in the Danish store in Vejle) causes lower temperatures in summer but initiates high humidity, of up to 70 % RH, and so a longer heating period combined with dehumidification is necessary.

With all variables considered, it became clear that the optimised building option could achieve very good conditions to store a collection without high costs. This result applies to both module types and both types of collection. A prefabricated double wall with optimised core insulation, concrete core cooling or under-floor heating (a smart and energy-efficient way of cooling and heating), floor insulation, a thick construction, low air exchange rate and user behaviour that supports passive conditioning can achieve a perfectly acceptable environment for a large component of every collection.
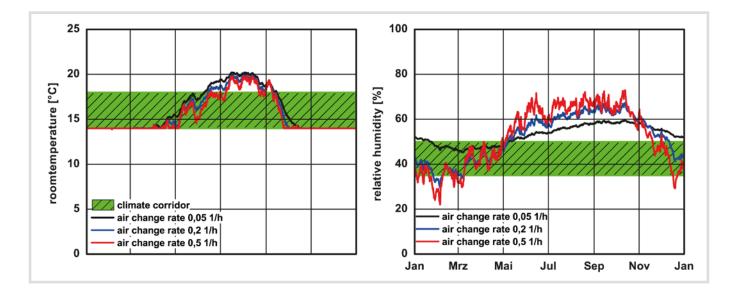
Under these circumstances it is possible to build a new modern storage building quickly and easily. In order to enhance sustainability it is necessary to optimise the indoor climate conditions, lower the energy consumption for ventilation and

dehumidification, reduce the maintenance cost and extend the effective life of the building. Therefore, some more expensive, but in the long term more effective, materials for core insulation and ground insulation are indispensable. This means increased investment in energy-optimised windows and gates (for the delivery area, workshop etc.), quality management during the construction period, a two-year-monitoring of the building construction, energy-optimised HVAC systems as well as the use of renewable energy sources (geothermal heat pump, solar thermal energy and photovoltaic cells). This upgrade concept is key to achieving sustainability as it can deliver low maintenance, zero-energy storage or archive buildings, which will last for a long time.

Figure 5 shows the annual energy consumption (electricity in yellow and gas in grey) for a painting storage module (right) and an archive module (left) for all simulated variations. The red line shows the profit of solar energy for the basic module of 300 m^2, which is an overall annual gain of 30000 kWh. The use of an archive wall construction reduces the energy consumption further because dehumidification is not necessary.

Wall construction/ archive wall

Super-insulated buildings can create dangerous levels of entrapped moisture and cause a high risk of mould growth or other humidity-induced damage. To solve the problem of construction material moisture being retained in a thick building with very low air exchange rates, a building material with little moisture must be identified for any of the construction elements that affect the indoor climate conditions such as walls, roofs and floors. The material must be feasible to produce on an industrial scale without generating additional costs. The prefabricated, pre-stressed concrete roof elements can be pre-treated before construction with a coating that avoids construction moisture. The concrete elements of the roof are limited to 15 % of the whole concrete mass of the building, so other roof elements can be made of materials that do not contain construction moisture. The floor, which for reasons of construction and stability is made of concrete poured in situ, can be isolated with a layer of epoxy resin. Only the prefabricated double wall elements must be reconsidered. For this reason, a study at the Fraunhofer IBP was initiated to find a dry concrete which exhibits

Figure 4. Influence of air exchange for the indoor climate variations
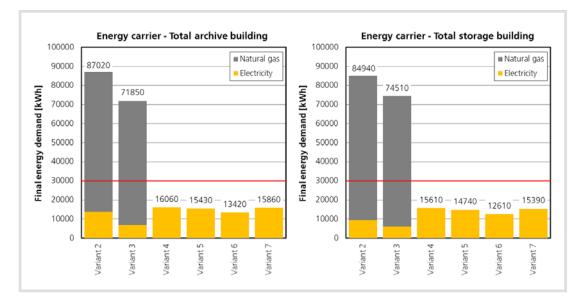
Figure 5. The annual energy consumption for a painting storage (right) module and an archive module (left) for all simulated variations

the German Standard DIN attributes but emits only a minimum of construction moisture because it contains only the water necessary for the hydration. A patent for this Archive concrete has been applied for. It can be used with the optimised construction option (double wall element with core insulation of phenol resin foam). The main advantage of the core insulation double wall element, with a U-Value of 0.14, and a dry concrete layer on the interior, is that it can lower and rationalise the energy consumption of the store or archive significantly.

Summary

The trend of current storage and archive projects is moving slowly in the direction of economic and efficient solutions. Unfortunately many stores and archives are still established with unnecessary expense and exceed their original budgets. This study and some good examples from the recent past demonstrate that it is possible to build effective buildings to store art collections and cultural heritage objects at a low cost. Traditional construction methods such as the archive concepts based on the Cologne or Schleswig model are obsolete and economically outdated. By incorporating industrial elements it is possible to build more favourable storage buildings quickly and efficiently. Of course, it will be necessary to evaluate specific conditions relating to building height, orientation and urban development but the basic construction method will remain the same. Furthermore, the Archive concrete saves energy on dehumidification, prevents mould growth, reduces the drying time and minimises construction moisture. The passively conditioned modular zero-energy storage and archive building is a product offered by the Fraunhofer IBP Spin off ModulDepot GmbH.

References

Knudsen, L.R., and Rasmussen M.H., 'Building a new shared facility for 16 museums and archives' in ICOM-CC 14th Triennial meeting The Hague, 12-16 September 2005: preprints, ed. I. Verger, James & James, London (2005) Vol. II 648–654.

Padfield, T., Larsen, P.K., Jensen, L.A., and Ryhl-Svendsen, M., 'The potential and limits for passive air conditioning of museums, stores and archives', in Museum Microclimates: Contributions to the

Copenhagen Conference, 19-23 November 2007, ed. T. Padfield and K. Borchersen, National Museum of Denmark, Copenhagen (2007) 191–198.

Sagstetter, M. R., 'Klimatisierungskonzepte in jüngeren Archivgebäuden in Deutschland', Archivalische Zeitschrift Bd. 86 (2004) 323–356.

Reimann, N., 'Bau und Einrichtung von Archiven – Erfahrungen und Beispiele aus Westfalen' in Texte und Untersuchungen zur Archivpflege, Bd. 20. LWL-Archivamt für Westfalen, Münster (2007).

DIN ISO 11799: Information und Dokumentation - Anforderungen an die Aufbewahrung von Archiv und Bibliotheksgut (2005).

Padfield, T., Larsen, P.K., Jensen, L.A., and Ryhl-Svendsen, M., 'Does a standard temperature need to be constant?', Meddelelser om Konserviering 1 (2010) 13–20.

Ryhl-Svendsen, M., Aasbjerg Jensen, L., Larsen, P.K., and Boehm, B., M., 'Ultra low energy museum storage', http://www.conservationphysics.org/icom-cc-pc2011/ryhlsvendsen_icom-cc20110103.pdf

Padfield, T., and Jensen, L.A. 'Humidity buffering by absorbent materials'. Submitted for publication, Nordic Building Physics 2011. www.conservationphysics.org/wallbuff/buffer_performance.pdf

Buddenbäumer, A., Studie zur Energieeffizienz eines neu zu entwickelnden modularen Kulturgüterdepots gemäß Monatsbilanzverfahren nach DIN V 18599. Bauliche und anlagentechnische Variantenrechnung zur energetischen Optimierung. Masters thesis, University of Augsburg (2011) (unpublished).

Author

Lars Klemm works at the Fraunhofer Institute for Building Physics in the Department of Climate. He coordinates research into retrofitting museums, storage and archive buildings. Since 2011 he has been leading the development of the Fraunhofer Spin off ModulDepot GmbH, including the patenting of the archive wall construction method. Within the ModulDepot GmbH he is also responsible for the customer advice service, marketing, sales, research and development.

Licence

New meets old – the requirements and limits of new collection facilities at the Museum für Naturkunde Berlin

**Peter Bartsch, Christiane Quaisser, Peter Giere,
Arwid Theuer-Kock and Norbert Feck**

Abstract

In commemoration of its bicentennial anniversary in 2010, the Museum für Naturkunde (Museum of Natural History) in Berlin, the largest of its kind in Germany, reopened a wing that was bombed and ruined at the end of World War II. This was the first in a planned series of works to adapt the museum's infrastructure to modern standards of collections care and energy efficiency. In the first phase, the ruined east wing of the museum was rebuilt as a high-security storage space. It was designed to meet safety requirements for storing the flammable fluid-preserved collection of zoological specimens in the context of a listed building and with the aim of optimal use of available space. This new facility now safely houses one million specimens preserved in 276,000 glass jars containing 80 tons of ethanol.

The second phase of the construction programme is now in the advanced planning stage. In the first phase temperature control was implemented predominantly for safety reasons, however, in the next stage the environmental conditions are designed to (i) meet the requirements of the 'dry' collections which are to be re-housed in a dedicated collection hall; (ii) minimise energy consumption by using the building's inertia and geothermal heating and cooling and (iii) optimise air exchange for both public and collection areas.

This article aims to describe the new wet collection building. It presents how the various demands of building, safety and collections care were balanced and optimised, guided by the principle of 'new meets old'. The paper also outlines the different approaches considered to adapt a historic museum building with a façade listed under monument protection to modern standards of collections care and energy efficiency.

Introduction

The Museum für Naturkunde in Berlin (MfN) holds a huge collection of about 30 million natural history objects, including minerals, fossils and zoological objects. The collection is preserved and stored in different ways according to the nature of the material. The majority are dry and wet (fluid) collections, though they exhibit a wide range of physical properties, logistical and conservation demands.

The collections of the MfN are much older than the current building, which was completed in 1889. The early core parts of the collections date back to several natural history cabinets of the late eighteenth century. They were combined as a research museum of the newly founded Berlin University in 1810. The available space in

the University's main building was outgrown within a few decades and a new location was chosen on the site of the former royal iron foundry at Invalidenstrasse. There, the older part of the present building, designed by August Tiede (1834–1911), was opened in 1889 after several drafts had been dismissed. The opening followed a long-running controversy over the building concept between the then director Wilhelm Carl Hartwig Peters (1815–1883) and the architect. Interestingly, Tiede had proposed the more modern concept of a store-like construction in 1875 [1, 2]. However, the director's concept for the new structure prevailed, a traditional museum entirely open to the public (Figure 1). Due to a quirk of history, the MfN was never completely open to the public as Peters' successor, Karl August Möbius (1825–1908), changed the concept again. The generous staircases were never used (Figure 2) and the upper floors remained closed to the public and have been used as scientific collection areas ever since. Until a few years ago, only the ground floor was accessible to the public, which housed a didactic exhibition designed for a general audience. This concept of separating exhibition from collection space, just emerging at that time, is still considered appropriate for the accommodation of the ever growing research collections of a large natural history museum [3–7].

As could have been predicted, the building soon became too small. The halls of the upper floors with their ornamented elevated ceilings were locked behind the scenes and the unused space above the collection cabinets contributed to the shortage of space (Figure 3). The design of the halls had originally been intended to provide well aerated and naturally illuminated exhibition space
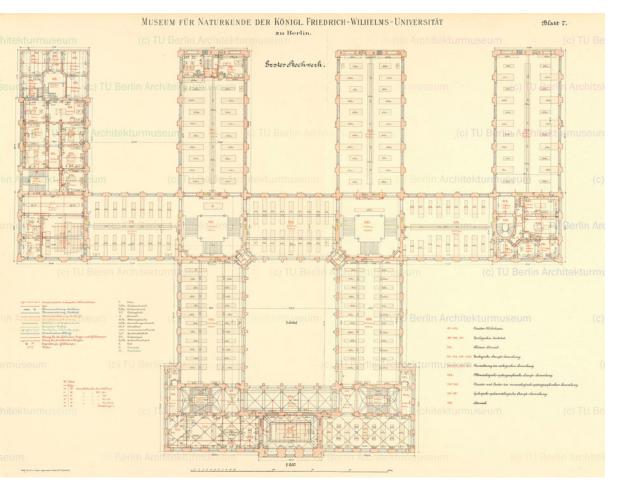
Figure 1. Original plan of the Museum für Naturkunde 1:200, first floor and layout chart of furniture
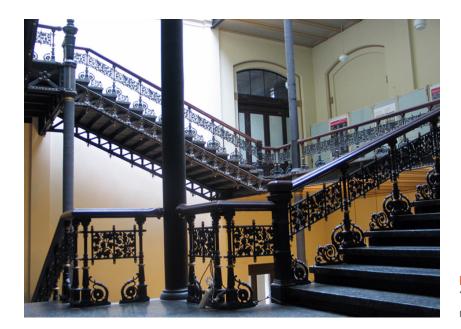
for scores of citizens eager to increase their knowledge. Large windows were the solution for providing ample lighting in the absence of suitable artificial illumination; in Berlin electrical lighting only became available from 1884 onwards, with the foundation of the Städtische Electricitätswerke. One of our collection halls had no electric lights until 2012.

To address the shortage of space, the northern wing was added in 1917. This part of the building maintained the separation of collection and exhibition space by including two additional floors within the same height profile as the original building, meeting the demands of that time for a collection store. This northern addition provided office space and now also houses laboratories (Figures 1–6). The only drawback with this addition was that the floors did not correspond to those of the original part of the museum building, not even on the exhibition level. This logistical problem presented a serious obstruction for disabled access and was not resolved until 2010 with the opening of the new eastern wing. The new wing now has a large freight and passenger elevator at the intersection of the two parts of the building, allowing all levels to be accessed.

As well as the collection space, Wilhelm Peters' 'all on show concept' has left us with the imperial architecture of five- to six-metre high collections halls, an impressive façade (around half of which consists of windows), and two grand internal staircases. Despite being closed off, the public have always been inclined to rush upstairs to see our fascinating research infrastructure and the endless rows of objects representing the natural diversity of the planet, past and present.

Technically, a major part of the building no longer fulfils the requirements of a modern facility for natural history collections. At the same time, however, the building provides insight for the public into the research collections in a very natural and elegant way. This concept of authentically presenting the scientific basis and methods of our work has become a guideline for rebuilding the museum. The rebuilding programme has been divided into several phases so the museum can remain functional during the long-term reconstruction, and due to limited funding. Future plans will need

to include a new collection storage area for the building, which can meet strict conservation guidelines.

Reconstruction of the eastern wing

In the years after completion of the northern addition, the collection halls became filled with new material. Luckily, war-time losses to the collection were comparatively minor, but the eastern wing of the original museum building was destroyed by a direct hit in an air raid in 1945 (Figure 5). Numerous plans to rebuild it failed due to shortage of money. Only the combined forces of the State of Berlin and the Federal Republic of Germany made possible the reconstruction of the ruin in time for the 200th anniversary of the museum. This reconstruction added urgently needed space: an effective usable area of around 5400 m^2 was achieved. In the planning phase it soon turned into a simple clear-cut approach dictated by the conservation and fire security requirements of the alcohol-preserved material, enforced by laws and regulations [8].

A directive from the nineteenth century specified that wet specimens should be separated from dry collections, with which they had previously been mixed [1]. However, this directive has rarely been fully implemented in any natural history museum due to lack of space, unfavourable logistics and a concern to store specimens according to biological classifications. The Museum für Naturkunde was no exception and it incorporated fully integrated wet and dry collections. The separation of these two types of collections was only implemented when the new eastern wing was constructed.

As the core of the eastern wing had been almost completely destroyed (Figure 5), a modern building could be constructed behind the extant original façade without any detriment to the historic architecture [9]. With up-to-date technical systems for environmental control, a moderately low constant temperature of 18 °C can now be maintained in the more frequently accessed upper research collections behind the scenes (Figure 4 right). In the lower area (Figure 4 left) of the lower gallery, which is open to the public, a transparent barrier and a temperature of

Figure 3. Collection hall on the second floor, the former Fish Hall, now empty and ready for restoration in the second phase of reconstruction

Figure 4. Wet collections in the reconstructed eastern wing: left ground-floor storage area with public gallery, right collection room on the upper level of the first floor. The 5 to 6 m high shelf system is horizontally divided by a lightweight grid-level, reminiscent of Thiede's first (1875) draft, with a rather industrial character

15 °C meet safety requirements (the inflammation point of 70 % ethanol is 18 °C) as well as avoiding temperature shocks when handling the material. Further details of conservation and safety specifications include an air exchange rate of 2.0 per hour and a nitrogen-based gas fire extinguishing system. In the original building the temperature extremes fluctuated between 13 °C in winter and 30 °C during hot summer periods, which led to a high evaporation rate of alcohol. Refilling glass jars was an important part of the every-day routine of collection management personnel. The adjacent northern part of the building with its more densely packed small rooms now provides air-conditioned collection space for dry collections of very high value with demanding conservation requirements. It also houses staff offices and laboratories for handling the collections. A conservation project supported by the Kulturstiftungen des Bundes und der Länder was also involved in creating this specialised storage space for the alcohol-preserved specimens by looking at improved collection management systems for wet collections [10]. This project mainly focused on replacing leaky glass jars, restoring and tightening of historical glass containers and the conservation of labels to ensure original information was retained securely.

The current project

With the reconstruction of the eastern wing, only a quarter of the functional area of the main building of the MfN has been renovated. Despite state of the art technology and insulation in the eastern wing, and despite renewal of numerous windows, energy consumption for running the estate is still high compared to former times, when the whole building was ventilated passively by convection through vertical chimneys (as in a termite mound) and heat loss through the leaky windows was mainly compensated by reducing the room temperature in winter.

The adverse interior environmental conditions in the halls housing various dry zoological collections, such as stuffed specimens, insects, bone, horn and skins, often require labour-

intensive temporary interventive conservation measures. Even paleontological material is not generally inert. Pyritic (fool's gold, FeS_2) and other components at high risk of weathering deteriorate under adverse environmental conditions. Environmental conditions and energy consumption are therefore the focus of the next stage of the reconstruction programme which is currently in an advanced planning phase (for a 6619 m^2 functional area). It is designed to:

1. Meet the environmental conservation requirements of the dry collections that will eventually be housed in the collection hall
2. Minimise energy consumption by using the building's inertia and geothermal heating and cooling
3. Optimise the storage volume, merge collections distributed over several areas of the building, make best use of the existing structure of the building for collections and provide nearby laboratory and office space for handling and research
4. Provide more space, improved infrastructure and more contact for the public with the research environment, to respond to increased public interest and growing visitor numbers
5. Optimise air exchange for both public and collection spaces.

Besides these criteria, there are a number of secondary requirements for the construction project. These include making some provision for the c. 600 guest scientists who visit the collections every year, the high intensity of scientific use of the specimens, the necessity for large-scale conservation programmes to safeguard particularly vulnerable areas of the collection, such as the large number of furs, stuffed specimens and skeletons, as well as the limited numbers of personnel in collection management. In 2008, several collection halls were equipped with mobile climate sensors and data loggers to obtain planning data. The monitoring focused particularly on collection halls that were to be re-developed in the second phase of rebuilding the museum: the Fish Hall, formerly housing the wet collection of fish on the second floor; the Mammal Skin Hall, underneath the Fish Hall on the first floor; and the Bird Hall, located on the first floor further west in the building (Figure 2). These halls are oriented north/

south and provide 570 m² area and 2840 m³ gross room volume, 566 m² area and 3400 m³ gross room volume, and 470 m² area and 2820 m³ gross room volume, respectively. The Bird Hall was recently equipped with double box-type windows incorporating new insulation glass (heat transfer coefficient of $U_g = 1.1$ W/(m²K)) that also excludes 90 % of ultraviolet radiation. Of course, the resulting energy transmission (U_w-value) will also depend upon the quality of the frame restoration and the insulation of the window soffit. This upgrade enabled an experimental assessment of the impact of the new windows on the room climate before any other measures were introduced (Figure 7).

Previous incidental environmental monitoring work has indicated that the generally dry climate of the collection halls is not detrimental for dried organic matter like mammal skins or mounts and stuffed birds. Optimum conservation conditions are achieved in a cool and dry environment with relative humidity (RH) between 30 and 55 % [11–13]. The literature indicates that the optimum for tooth-bearing vertebrate skulls and mounted specimens (dermoplastic preparations) is at the upper end of this range, and our experience suggests that skins, chitin, horn material and uncleaned skeletons is at the lower extreme.

In terms of the MfN environment, particular causes for concern were the high summer temperature extremes measured (Figure 7) and the rapid changes of room temperature and relative humidity which followed external weather conditions. Both are disastrous for long-term conservation. The daily rhythm of temperature and relative humidity as seen in figure 7 leads to continuous stress on the material due to expansion and contraction driven by changes in moisture. These processes are particularly detrimental to specimens that consist of horn, bone or dentine, or collagen fibril networks [14]. In particular, mammal skins are endangered by increased air moisture content as residual acid from incomplete tanning processes may be mobilised [15]. As illustrated by figure 8,
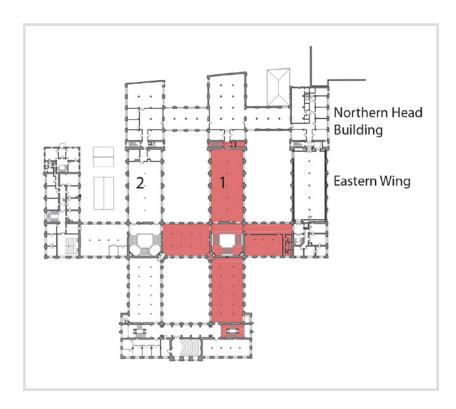
Figure 6. Survey plan of the MfN today 1:400, first floor: 1 Mammal Skin Hall, 2 Bird Hall; Fish Hall is on top of position 1 in the second floor, the area of the second phase of reconstruction in red
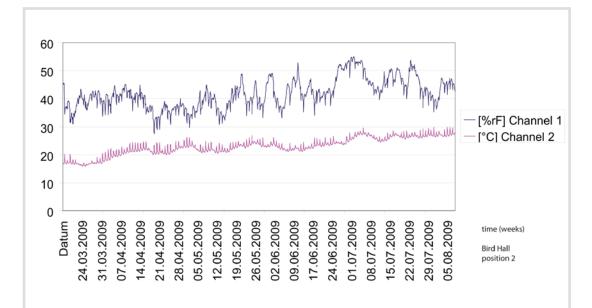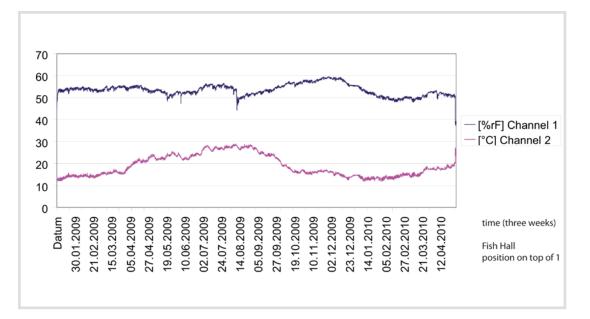
Figure 7. Top: Part of the record of temperature and relative humidity in Mammal Skin Hall (cf. Fig. 6, position 1); middle: Part of the record of temperature and relative humidity in Bird Hall (cf. Fig. 6, position 2) before window restoration; bottom: – after window renovation

the conditions in the upper halls on the second floor are worse
than those on the first floor. Being more exposed to sunlight, they
usually have higher annual extremes of temperature and as the
condition of the windows is even worse in these halls, they also
tend to be wetter. Our predecessors as curators were well advised
to identify these areas for storage of the larger 'wet' collections.
Leaky windows also increase the danger of pest infestation. Pests
are best prevented by tight windows and cabinets and by low
temperature storage. As expected, the window renovation in the
Bird Hall did not lead to any reduction in the summer temperature
extremes, but the overall pattern of temperature and relative
humidity fluctuation became much more even (Figure 7 bottom).

By comparing these environmental monitoring data with the
recorded external weather conditions (monitored regularly by the
Technical University of Berlin's Institute of Meteorology, courtesy
of Dr. Klaus Müller) it was possible to simulate the climate in the
collection halls under several different technological regimes and
use scenarios. The aim of the simulation analysis was to find the
optimum balance between the requirements of the collection on
one hand and the energy consumption measured by the annual
energy costs on the other. Therefore, a simulation model of the
whole museum was compiled. Typical hourly weather data at the
location were used as boundary conditions (TRY test reference year
prepared by the Germany's National Meteorological Service). The
software calculates solar altitude and resulting solar radiation
on the façades of the building. With this model it was possible
to simulate room conditions (temperature and humidity) under
different weather conditions to investigate the effects of various
scenarios, for example, different glazing and sun protection
devices at the windows, natural infiltration, internal insulation, the
presence of visitors or different building elements. The heating
and cooling loads and the annual energy consumption were also
calculated. To find the best solution, the simulation results were
statistically analysed (Figures 9 and 10) and discussed between
the MfN team and the architect. The analysis demonstrated that
the great thickness of the external walls is an advantage for the
museum as the large storage mass reduces short- and medium-
term temperature fluctuations. Internal insulation of the walls
would reduce this positive balancing effect. Consequently, it was
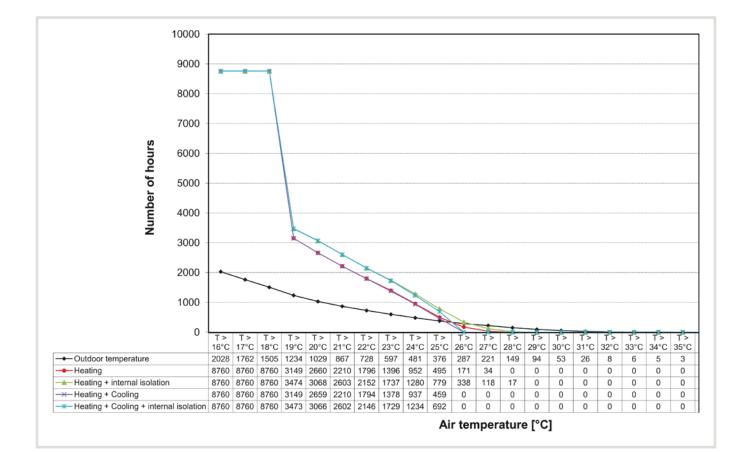
decided that no internal insulation would be installed although this will result in slightly higher annual energy consumption. An in-wall heating and cooling system was selected to reduce energy costs. It requires only a low supply temperature delivered by a heat pump which taps into geothermal energy taken from underground loops.
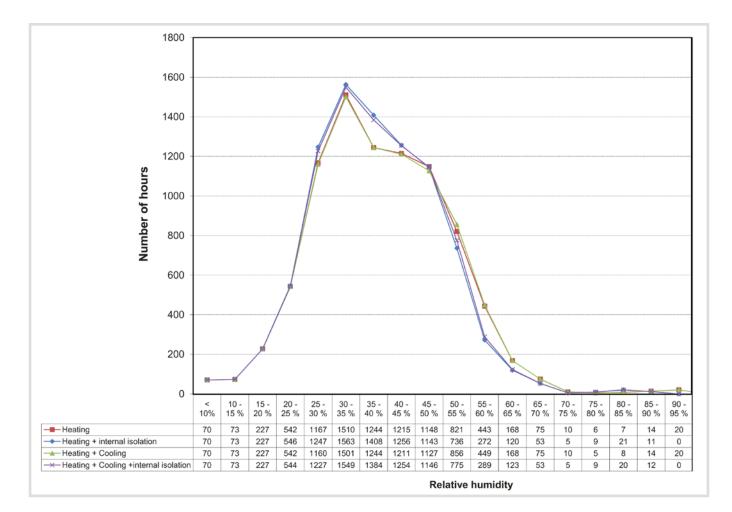
Once thermal conditions were under control the attention was turned to the humidity trend. As the recent measurements illustrated, it is important to reduce the leakiness of the old windows. Low natural infiltration is necessary to maintain a distinction between the indoor climate and the external weather conditions, particularly in order to reduce short-term fluctuations in air humidity. The effects of different rendering materials and visitor numbers on the humidity trend were analysed with a special simulation model (Figures 11 and 12). The simulation shows that the type of rendering has a high influence on the humidity trend. Loam and clay renderings reduce the amplitudes of the relative humidity much more effectively than normal plaster [16]. On the evidence of these data and the measurements from the Bird Hall and Fish Hall it was decided to install a loam or clay rendering and to abandon technical humidification and dehumidification systems. The loam rendering can also be combined with the wall heating and cooling system. The second consideration was that the simulation demonstrated visitor groups of ten or more people increase the relative humidity considerably (Figures 11 and 12). It is therefore advantageous to encourage visits to the collection halls during dry winter periods, and to close the spaces to the public during wet summer periods.

In summary, the analysis of room conditions by computer simulations to test the influence of various approaches was found

Figure 9. Cumulative frequency of the temperature in the Mammal Skin Hall, employing large area wall heating and cooling (violet) using the inertia of the building and adding internal insulation (blue)

	T > 16°C	T > 17°C	T > 18°C	T > 19°C	T > 20°C	T > 21°C	T > 22°C	T > 23°C	T > 24°C	T > 25°C	T > 26°C	T > 27°C	T > 28°C	T > 29°C	T > 30°C	T > 31°C	T > 32°C	T > 33°C	T > 34°C	T > 35°C
Outdoor temperature	2028	1762	1505	1234	1029	867	728	597	481	376	287	221	149	94	53	26	8	6	5	3
Heating	8760	8760	8760	3149	2660	2210	1796	1396	952	495	171	34	0	0	0	0	0	0	0	0
Heating + internal isolation	8760	8760	8760	3474	3068	2603	2152	1737	1280	779	338	118	17	0	0	0	0	0	0	0
Heating + Cooling	8760	8760	8760	3149	2659	2210	1794	1378	937	459	0	0	0	0	0	0	0	0	0	0
Heating + Cooling + internal isolation	8760	8760	8760	3473	3066	2602	2146	1729	1234	692	0	0	0	0	0	0	0	0	0	0

Air temperature [°C]

	< 10%	10 - 15 %	15 - 20 %	20 - 25 %	25 - 30 %	30 - 35 %	35 - 40 %	40 - 45 %	45 - 50 %	50 - 55 %	55 - 60 %	60 - 65 %	65 - 70 %	70 - 75 %	75 - 80 %	80 - 85 %	85 - 90 %	90 - 95 %
Heating	70	73	227	542	1167	1510	1244	1215	1148	821	443	168	75	10	6	7	14	20
Heating + internal isolation	70	73	227	546	1247	1563	1408	1256	1143	736	272	120	53	5	9	21	11	0
Heating + Cooling	70	73	227	542	1160	1501	1244	1211	1127	856	449	168	75	10	5	8	14	20
Heating + Cooling +internal isolation	70	73	227	544	1227	1549	1384	1254	1146	775	289	123	53	5	9	20	12	0

Relative humidity

Figure 10.
Frequency distribution of the prospective relative humidity in the Mammal Skin Hall employing large area wall heating and cooling (green) using the inertia of the building and adding internal insulation (violet)

to be an appropriate tool to guide decision making during the planning process and it stimulated target-oriented discussions between all parties involved.

Conclusion

Our conclusions for the planning process were that it is feasible to introduce an energy-saving heating and cooling system driven by geothermic energy which takes advantage of the inertia of the building, if summer maxima inside the collection halls are permitted to reach 25 °C. It is expected that the temperatures can be kept below 20 °C during most times of the year (29429 hrs, figure 11). We would allow a gradual temperature change and permit the temperature to drop to 15 °C during winter. The only restrictions are the health and safety regulations ('Arbeitsstättenrichtlinie') and the structural-physical limitations of condensation and heat transfer between neighbouring rooms. This approach would contribute to saving energy and avoiding steep drops in relative humidity.

The monitoring data for annual relative humidity in the Mammal Hall over recent years (Figure 7 top) are actually better than the pattern indicated by the simulation (Figure 9); RH exceeded 55 % only in late summer. This may be a result of the huge volume of fur materials actually present in the collection hall, which absorb moisture. Extremes and fluctuations of relative humidity would be mitigated further by a humidity-buffering layer of loam rendering and tightly-fitting cabinet doors. The alternative solution of adding internal insulation to the outer walls would be

complicated and costly in an architecturally significant monument and demonstrates only marginal advantages in the simulations (Figures 11 and 12). Furthermore, this intervention would minimise the favourable influence of the inertia of thick walls of the original museum building. As demonstrated by the positive impact of the window restoration in the Bird Collection Hall, we will aim to achieve an appropriate conservation environment by combining all these measures with effective light and UV protection in the box-type windows. Previously, the extremely low temperatures in the current building were effective at preventing pest infestations, retarding decay processes and hindering the development of bacteria, fungi, and dermestid (i.e., museum beetle) larvae. However, tightly-fitting cabinets and well-sealed windows combined with an integrated pest management system that includes constant pest monitoring by collections management personnel will remain essential barriers against the influx of pest organisms.

Our optimistic conclusion is that the collection halls can be used for storage of the dry collections at reasonable energy cost. As a bonus, the collection halls can also be opened to guided tours of visitors in winter without compromising the environmental conditions.

Acknowledgements

References

[1] Tiede, A., Museumsbaukunde, Wilhelm Greve, Berlin (1898) 1–89.

[2] Helbig, J., 'Entwurfs- und Baugeschichte des Museums für Naturkunde', in Klasse, Ordnung, Art – 200 Jahre Museum für Naturkunde Berlin, ed. F.S. Damaschun, S. Hackethal, H. Landsberg, H. Leinfelder, Basilisken-Press, Rangsdorf (2010) 28–32.

[3] Möbius, K.A., 'Rathschläge für den Bau und die innere Einrichtung zoologischer Museen', Zoologischer Anzeiger 7 (1884) 378–383.

[4] Möbius, K.A., 'Rathschläge für den Bau und die innere Einrichtung zoologischer Museen.', Zentralblatt der Bauverwaltung 4 (1884) 420–421.

[5] Goode, J.B., 'The museums of the future', Report of the National Museum, Smithsonian Institution 1888-1889 (1891) 427–445.

[6] Goode, J.B., The Principles of Museum Administration, Reprint from the Annual Report of the Museums Association, Coultas & Volans, York (1895).

[7] Jahn, I., 'Der neue Museumsbau und die Entwicklung neuer museologischer Konzeptionen und Aktivitäten seit 1890', Wissenschaftliche Zeitschrift der Humboldt-Universität zu Berlin, Math.-Nat. R. 38 (1989) 287–307.

[8] Bartsch, P., and Neuhaus, B., 'Der Wiederaufbau des Berliner Museums für Naturkunde.', Museum Aktuell 179 (2011) 13–16.

[9] Diener, R., ʾKontinuität und Neufassung – Die Renovierung des Ostflügelsʾ, in Klasse, Ordnung, Art – 200 Jahre Museum für Naturkunde Berlin, ed F.S. Damaschun, S. Hackethal, H. Landsberg, R. Leinfelder, Basilisken-Press, Rangsdorf (2010) 60–61.

[10] Neuhaus, B., Allspach, A., Bartsch, P., Burckhardt D., Coleman, C.O., Fries, I., Fuch, R., Gudo, M., Kotrba, M., Mentjes, M., Moore, S., Neumann, D., Oberer, C., Potthast, A., Riedel, J., Rudolf, R., Schnalke, T., Schönbohm, D., Schuda, M., van Dam, A., and Widulin, N., KUR-Projekt: Aufbau und öffentliche Kommunikation eines wissenschafts-basierten Sammlungsmanagements für naturkundliche Nasssammlungen, http://dx.doi.org/10.5165/hawk-hhg/epublication/44 (2012) 1–32.

[11] Stolow, N., 'The action of environment on museum objects Part I.: humidity, temperature, atmospheric pollution', Curator 9 (1966) 175–185.

[12] Stansfield, G., Mathias, J., and Reid, G., Manual of Natural History Curatorship, HMSO, London (1994) 1–306.

[13] Carter, D., and Walker, A.K., Care and Conservation of Natural History Collections, Butterworth Heinemann, Oxford (1999) 1–226.

[14] Fitzner, K., and Hilbert, G.S. 'Klimatisierung', in Sammlungsgut in Sicherheit, ed. G.S. Hilbert, Gebr. Mann Verlag, Berlin (2002) 127–242.

[15] Troxler, M., and Meier, C, 'Der säurebedingte Zerfall von Bälgen und Fellen. Ein Beitrag zur Restaurierung von alaungeschädigtem Balgmaterial (Felle)', Der Präparator 49 (2003) 49–59.

[16] Ziegert, C, 'In Balance – Zum Sorptionsverhalten von Lehmbaustoffen', db deutsche bauzeitung 2 137.2 (2003) 73–80.

Authors

Peter Bartsch (author for correspondence) is Curator of Ichthyology and Head of the Department of Collections at the Museum für Naturkunde (Museum of Natural History, MfN) in Berlin. He is responsible for the building reconstruction programme. Email: peter.bartsch@mfn-berlin.de

Christiane Quaisser is an ornithologist and responsible for collection initiatives at the Museum für Naturkunde Berlin. Conservation science and collections development are major elements of her work. Email: christiane.quaisser@mfn-berlin.de

Peter Giere is Curator of the Embryological Collection at MfN. Besides his curatorial tasks and research in mammal development and systematics, he is involved in various activities to promote the preservation of natural history collections. Email: peter.giere@mfn-berlin.de

Arwid Theuer-Kock is a physicist and managing director of 1plus Consult GmbH, the consulting company for energy design and building physics. Email: arwid.theuer-kock@1plus-consult.de

Norbert Feck is a building services engineer and a mechanical engineer specialising in energy systems. He is experienced in the design of HVAC systems as well as passive structural measures to avoid active energy use. In addition he is a leading engineer in dynamic simulation application. Email: Norbert.Feck@1plus-consult.de

Image credits

Figure 1. © Architekturmuseum TU Berlin
Figure 6. © Diener&Diener 2010
All other figures. © Museum für Naturkunde, Berlin

Licence

The use of underground structures as a solution towards sustainable museums in the Mediterranean basin

Dimitrios Karolidis

Abstract

The underground museum at the Roman Forum site in Thessaloniki is assessed under the energy efficiency principle of sustainability. The environmental parameters of temperature and relative humidity, the level of control over these parameters and the energy consumed to manage the exhibition environment are monitored and recorded over a period of seven months. A comparison is made with similar data gathered from a ground-level museum in close vicinity. Results indicate that a more stable exhibition environment is achieved at the Roman Forum museum with less energy consumption and operating expenditure than in the ground-level museum. If wider climate control specifications are adopted than the '20 °C plus or minus 2 °C temperature and 50 % plus or minus 5 % RH all year-round' rule of thumb, particularly for object collections made of less vulnerable materials such as ceramics, glass, stones and mosaics, underground structures may be a solution towards sustainable museums in the Mediterranean area.

Introduction
Need for sustainability in museums

Sustainability is associated with the term 'sustainable development' as used in the report of the World Commission of Environment and Development issued in December 1987 [1]. According to this report 'sustainable development is a practice to meet the needs of the present without compromising the ability of future generations to meet their own needs'. Sustainable development aims to provide for the fundamental needs of humankind while preserving the natural systems of life on earth [2]. Museums are organizations which operate within an environmental, economic and social context and their modus operandi has an impact within this context. Museums consume energy and money in order to meet their purpose and mission, which includes the protection of the cultural inheritance of humanity through the provision of a protective environment for display and storage [3]. Agents of deterioration within the museum environment are controlled according to a set of core principles or standards which have been developed over the years by individuals or groups qualified in preventive conservation. To achieve these standards management systems and equipment are required which consume fossil fuel. Most of this energy consumption is for heating, ventilation, air conditioning (HVAC) and lighting purposes. The quest to meet the recommended environmental conditions leads to an excessive waste of energy [4]. As international environmental targets become more strictly enforced, museums will experience increasing pressures to reduce their impact on the natural environment by adopting processes which are environmentally responsible and resource efficient [5].

The idea of using the underground as museum space

The expansion of cities through uncontrolled construction is congesting the surface of the planet and the resultant loss of natural cover along with the burning of fossil fuels are the two main human activities contributing to global warming [6]. The earth needs large amounts of open space in order to renew its natural systems. A possible solution may be the use of the underground as a new space for urban expansion, including museum development. The exploitation of subterranean space for purposes ranging from infrastructure to living quarters is an ancient practice. Caves and natural cavities are examples of early residential uses [7]. The hypogeous ancient Greek and Roman aqueducts are examples of infrastructure and early sustainable practice [8]. The Macedonian and Thracian tombs, subterranean burial chambers with colorful wall paintings, are further illustrations from the sphere of art history. The works of art inside such constructions have survived until the present day without any human intervention to alter environmental parameters [9]. A close inspection of these examples demonstrates that in every case the building envelope was used for the management of the interior conditions. It is possible that, in some climatic regions, such practices may eliminate the requirement for environmental control management systems. The concept of the underground museum offers the potential for achieving ideals of sustainability through environmental control schemes which would consume less energy than conventional museums.

Methodology of research

The aim of this research is to assess the potential of underground structures to provide a solution for sustainable museums in the Mediterranean basin. This is accomplished by investigating the hypothesis that underground museums perform better than ground-level museums in meeting suggested environmental parameters, consuming less energy and with a lower environmental impact and so operating in a more sustainable way. More specifically, the relationship between energy costs and the level of environmental control in underground museums and ground-level museums is determined and the findings are compared. The levels of temperature and relative humidity (RH) are measured in the underground museum of the Roman Forum in Thessaloniki and in the Archaeological Museum of Thessaloniki (AMT), which is a ground-level museum. Both sites are in close proximity so they are exposed to the same climate annually. The collected data is assessed and compared with the energy consumption associated with the operation of the engineering systems providing these environmental parameters. The temperature and RH were chosen as the primary data for investigation because controlling these parameters with the use of HVAC systems is the main reason for energy consumption in museums and consequently the key to sustainable practice. The findings apply primarily to the Mediterranean basin due to the fact that the selected museums are located in Greece which, according to the Köppen-Geiger climate classification system, lies in the 'Dry Summer Subtropical' climatic zone [10]. This zone is known as the Mediterranean climate and is characterized by wet and cool winters and dry and hot summers. The extremities in yearly weather conditions of this type of climate affect the environmental conditions in museums and consequently the control over them; thus, the research will reflect upon this region.

Date	Heating Degree Days	Cooling Degree Days
January	315.4	0.1
February	244.8	0.7
March	208.9	11.0
April	71.1	9.0
May	13.8	83.0
June	0.1	181.0
July	0.2	275.8

| ▮ Heating season | ▮ Heating season | ▮ Heating season |

Table 1. The engineering climate data from the city of Thessaloniki collected for the research period

Data collection started in January and ended in August, covering winter, spring and summer in Thessaloniki. The sites provided the total floor area of the buildings, the type of climate management system installed and the energy bills for the research period. AMT uses a sophisticated multi zone HVAC, while the museum of the Roman Forum uses a two zone, variable volume HVAC system. Once the costs and consumption of energy for the climate management system during the research period were calculated, they were divided by the total floor area of the building to determine the cost and consumption of energy per square meter.

The time formats over which the sites are compared are the heating and cooling degree days and the heating and cooling seasons instead of the typical winter, spring and summer format. This measurement reflects the demand for energy needed to heat or cool a building and the seasonal climate changes are presented in numbers. The heating season is when cold temperatures outside necessitate museum heating (the more heating degree days, the more heating is required), the cooling season is the opposite (the more cooling degree days, the more cooling is needed) and the mixed season is when there is a need for both heating and cooling (Table 1).

The two museums change their systems of climate management for the different engineering climate seasons (set points of temperature and RH on HVAC systems) and this is an additional reason for analyzing the recorded data and energy costs separately for each season.

Comparative analysis of the sites

For each individual season (heating, cooling and mixed) the following three categories of graphs are created so that the data can be visually interpreted:

1. A bar chart of the frequency and the cumulative frequency of temperature/RH ranges of atmospheric air and of the conditions inside the two museums. This analysis shows which ranges of temperature/RH are reached more often (frequency) in every site and their running total (cumulative frequency) in comparison with the outside climatic conditions. This chart represents the level of control over the environmental conditions with the use of the HVAC systems (Figure 1).

2. A scatter chart of the performance index (PI) [11, 12] of the two museums versus the following preventive conservation guidelines: Strict [13], National Museum Directors Conference (NMDC) [14],
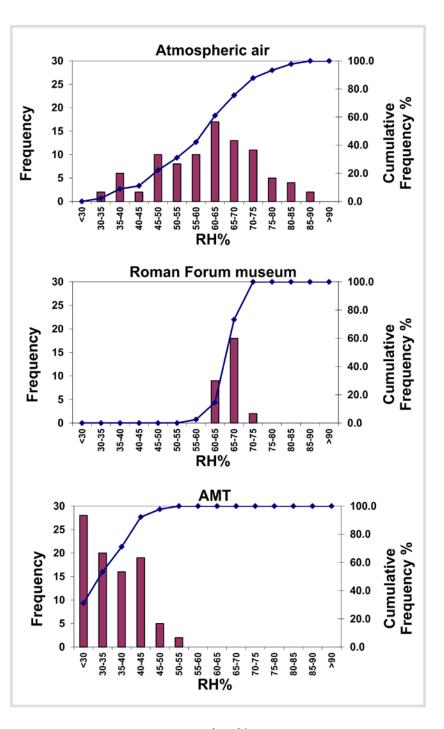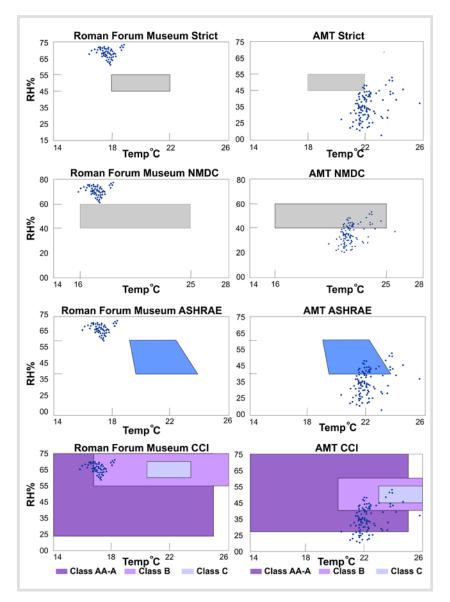
Figure 1. The frequency and cumulative frequency of temperature/ RH ranges of atmospheric air and of the air inside the two museums during the heating period

Canadian Conservation Institute (CCI)/American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Classes of control [15] and the ASHRAE 55-2004 Standard for human comfort [16] (Figure 2).

The strict guidelines of 20 °C plus or minus 2 °C temperature and 50 % RH plus or minus 5 % RH all year-round within the museum environment are chosen because they have been the norm in preventive conservation for decades. The NMDC guidelines of a stable temperature in the range of 16 to 25 °C and a stable relative humidity (RH) in the range of 40 to 60 % are selected because they have been developed fairly recently in consultation with UK conservators, the UK Institute for Conservation (ICON) and the National Trust as a step towards a less energy-intensive approach to collections care. The CCI/ ASHRAE Classes of control are included because they have been developed through conservation

research on 'quality' climate control. The AA-A class permits short-term fluctuations of plus or minus 5 % RH and plus or minus 2 °C, with a seasonal set point change in temperature of plus or minus 5 °C, while no seasonal change in RH set point is allowed. This kind of control over collections requires the most resources and a well-built space with climate control. The B class of control allows short-term fluctuations of plus or minus 10 % RH and plus or minus 5 °C, with a seasonal temperature change of up to 10 °C. The temperature cannot be allowed to rise above 30 °C but can fall as low as necessary to maintain RH control. The B class of control is suggested as a reasonable target for collections in historic buildings that can tolerate the intervention of some mechanical systems but are susceptible to changes in humidity conditions. The C class of control permits RH in the range of 25 to 75 % all year and temperatures below 25 °C. Finally, the ASHRAE 55-2004 Standard for human comfort in public spaces is chosen because museums often adopt it, prioritizing human needs over collections care. This standard permits temperatures in the range of 20 to 28 °C and RH in the range of 30 to 60 % in winter and summer seasons. The European Directive for Energy Performance of Buildings approved the Criteria for the indoor environment including thermal, indoor air quality (ventilation) light and noise

Figure 2. The performance index of the two museums against the preventive conservation guidelines during the heating period

draft standard at the beginning of 2006. This draft is still under an international review process, and so is not used in this paper [17]. By the time this research was being completed, the new BSI Group Standard, PAS 198:2012, Specification for managing environmental conditions for cultural collections was about to be published, therefore it was not possible to include it here.
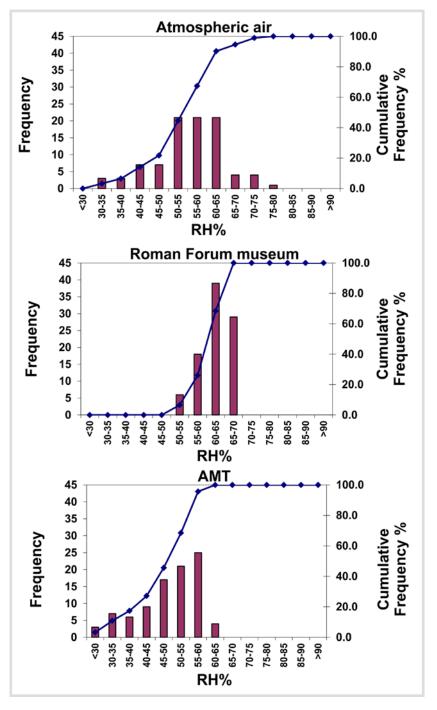
The PI is the percentage of the recorded data of temperature and RH which fall in the region defined by the numeric values of temperature and RH suggested by the aforementioned preventive conservation guidelines for every season. The suggested standards are displayed with the use of coloured polygons. The average daily values of temperature and humidity in the two museums are shown as clustered spots, their occurrence inside the shape boundaries is measured and the percentage of this occurrence is calculated (PI). The deviations from the suggested standards are estimated and the performance of the two sites in compliance with the guidelines and standards is presented.

3. A bar chart of the energy consumed in the two museums versus the performance index achieved in every category of guideline. These graphs show which museum requires the most energy and money expenditure and what level of environmental control is achieved in each site (Figure 3).

Discussion

The frequency and cumulative frequency of temperature and RH ranges is more limited (smaller ranges of these parameters appear) in the Roman Forum Museum than in AMT, suggesting a more efficient level of environmental control in the former. During the heating period the recorded data from the Roman Forum museum shows that two ranges of RH are favoured (60 to 65 % and 65 to 70 %) with 65 to 70 % being dominant, while AMT shows a diversity of range frequencies, with below 30 % being the dominant range (Figure 1). During the mixed period, the recorded data from the Roman Forum Museum show that three range regions are favoured (60 to 65 %, 65 to 70 % and 70 to 75 %) with 70 to 75 %

being the dominant one; while AMT shows a diversity of value range frequencies, with the regions 30 to 35 % and 40 to 45 % being equally dominant. Finally, during the cooling period the data from the Roman Forum Museum shows that three regions are favoured (55 to 60 %, 60 to 65 % and 65 to 70 %) with 60 to 65 % being dominant; while AMT presents a smaller level of environmental control (more ranges appear) with the 55 to 60 % range being the most prevalent (Figure 4). This data also shows that the humidity in the Roman Forum Museum is high during the whole research period, contributing to a slightly damp atmosphere inside the site. This may lead to a biological attack in the future because molds and insects thrive at elevated RH and moderate temperatures. During the research period no signs of biological activity were evident inside the Roman Forum Museum, probably because excursions above 65 % RH were restricted to a few days or less

Figure 4. The frequency and the cumulative frequency of temperature/ RH ranges of atmospheric air and of the air inside the two museums during the heating period
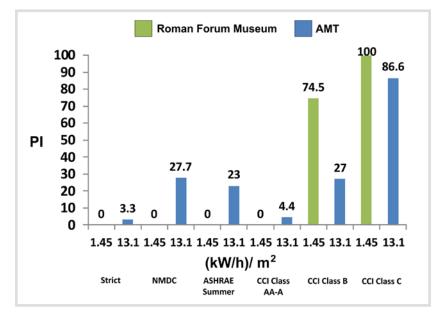
while dew points were low (as calculated from the temperature and RH readings) [18]. This is a disadvantage of underground space usage and an issue that needs constant monitoring and further investigation.

The comparison of the two museums using the performance index is probably the most crucial one because it introduces the terms and conditions under which the research hypothesis can be supported. The recorded data shows that the usage of underground space for museum purposes provides significant energy savings through more efficient and economical control of the installed HVAC systems compared with a ground-level museum. During the heating period, the Roman Forum Museum failed in adhering to the strict, NMDC guidelines and ASHRAE Winter standards but delivered a 74.5 % CCI class B and a 100 % CCI class C performance, while AMT also performed poorly, delivering a 4.4 % CCI class AA-A, a 27 % CCI class B and an 86.6 % CCI class C performance (Figure 2). The Roman Forum Museum consumed 1.45 (kW/h) per m^2 of energy and spent 0.20 € per m^2, while AMT consumed 13.1 (kW/h) per m^2 of energy and spent 1.84 € per m^2 (Figure 5).

In the mixed season, the Roman Forum Museum failed in adhering to the strict, NMDC guidelines and ASHRAE Winter standards but delivered a 100 % class B and class C performance, while AMT performed slightly better but still poorly. The Roman Forum Museum consumed 0.26 (kW/h) per m^2 of energy and spent 0.03 € per m^2 while AMT consumed 3.64 (kW/h) per m^2 of energy and spent 0.61 € per m^2.

Finally, in the cooling season, the Roman Forum museum failed in following the strict, NMDC guidelines and ASHRAE summer standards, but delivered a satisfactory CCI class AA-A performance (45 %) and an optimal class B and class C performance. AMT also presented a low performance, delivering an average CCI class AA-A and class C performance (37 % and 43 % respectively) and a very high class B performance of 81.3 % (Figure 6). During this season, the Roman Forum museum consumed 3.84 (kW/h) per m^2 of energy and spent 0.52 € per m^2 while AMT consumed 25.7 (kW/h) per m^2 of energy and spent 3.60 € per m^2 (Figure 3).

These findings raise the question of which set of guidelines should be used as a reference for judging the performance of the two sites and consequently for setting sustainability criteria against which the research hypothesis can be tested. If the strict and NMDC guidelines are used as reference, then both museums would need to adjust their environmental control using HVAC systems, probably at significant energy and financial cost, as they both failed to achieve the standards established in the guidelines throughout the entire research period. If the CCI/ ASHRAE classes of control are used then an underground museum could easily and sustainably achieve a control class B and C with minimal consumption of energy and expenditure of money. A class B level of control allows short-term fluctuations of plus or minus 10 % RH and plus or minus 5 °C, with a seasonal temperature change of up to 10 °C, while the temperature cannot be allowed to rise above 30 °C but can fall as low as necessary to maintain RH control. A class C level of control allows RH ranges of 25 to 75 % year-round and a temperature usually below 25 °C. These specifications raise the question of which types of historic artifacts can withstand such an environment and introduce a second set of conditions which need to be met in order to support the original research hypothesis. According to CCI/ ASHRAE guidelines, classes B and C present little risk of damage to medium vulnerability objects but a high risk of damage to high vulnerability artifacts. These specifications
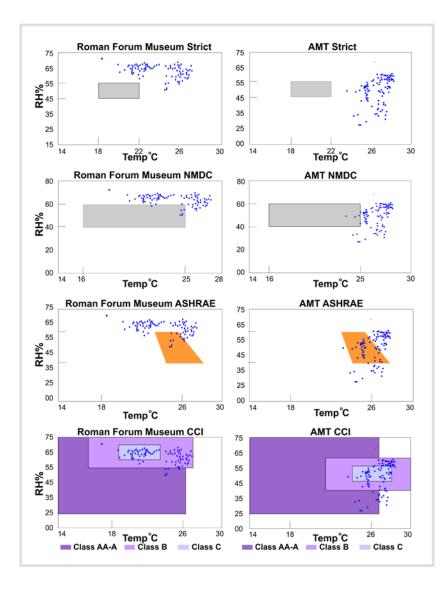
Figure 6. The performance index of the two museums against the preventive conservation guidelines during the cooling period

use Stefan Michalski's work [19] to classify medium and high vulnerability according to types of wooden artifacts, which is not useful for the majority of museum collections. Instead Barbara Reeve's aggregate tables can be more illuminating in determining the vulnerability or safety of various types of materials in various ranges of RH and temperature [20]. Figure 7 shows the safe ranges of RH and temperature for different types of materials.

These figures can be misleading since they refer to modern rather than archaeological materials but they can be used as rough guides. According to these tables, museum collections comprising mostly of ancient ceramic and stone artifacts (which applies to the majority of museums in the Mediterranean basin), can withstand a class B and C exhibition environment. Proper environmental conditions for display and storage of more vulnerable archaeological materials are illustrated in table 2 [21]. Objects made of such materials can be further protected by being placed in confined spaces with microclimate control (e.g., display cases with bulk desiccants or Miniclima devices).

The suitability of a class B and C exhibition environment in an underground museum is supported by the limited temperature and RH fluctuations which prevent deterioration processes such as salt efflorescence and crystallization. This is the case in the Roman Forum museum where the majority of the displayed objects are made of clay and stone, while the more vulnerable ancient metal and glass objects are displayed in small cases with controlled microclimates.

Finally, both sites performed disappointingly against the ASHRAE Winter and Summer guidelines for human comfort. During the heating period, the Roman Forum museum achieved a 0 % PI and
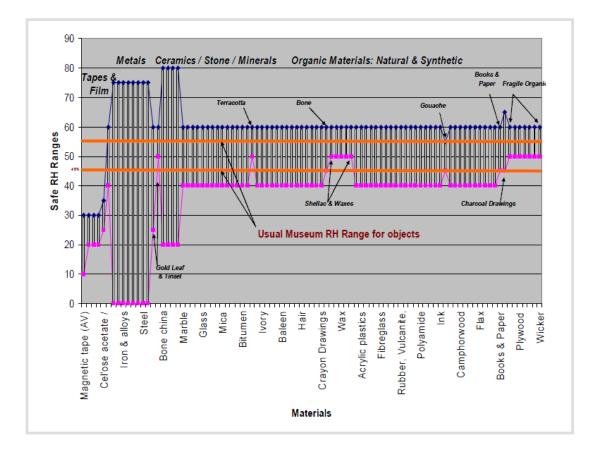
Figure 7. Safe relative humidity ranges for different types of materials found in museum collections. Adapted from [20]

Table 2. Proper environmental conditions for the display and storage of more vulnerable archaeological materials. Adapted from [21]

Materials	Ambient Temperature [°C]	Ambient Relative Humidity [%]	Microclimates (where needed)	Indications of Active Decay
Metals (non-ferrous)	18 (min. 10 max. 25)	50 (part of mixed collection)	Less than 35 %	Tarnish on polished surfaces
		35 (dedicated metal collection)	Not applicable	Powdering
Metals (ferrous)	As above	50 (part of mixed collection)	Less than 15 %	Fresh corrosion products
		35 (dedicated metal collection)	Not applicable	'Weeping', cracking
Organic materials (bone, leather, wood, etc.)	As above	50 (part of mixed collection)	Take advice	Mould & fungus Cracks, warping, flaking
Waterlogged & wet stored materials	10 (the cooler and darker, the better, but always above freezing)	Not applicable	100 %	Embrittlement, shrinkage, drying out and breakdown of adhesives, fading, bleaching
Inorganic materials (pottery, stone, glass, etc.)	18 (min. 10 max. 25)	50 (part of mixed collection)	Take advice	Stone: efflorescence – salts coming out Ceramics: flaking glazes, powdering fabric Glass: 'weeping' – wet surface, 'crizzling' – fine cracks, glass becomes opaque
Composites (e. g. metals and organics)	Take advice. The climate should be determined by the most unstable and/or archaeologically significant part of the object.			

AMT achieved a 23 % PI. During the mixed period (the overlapping winter and summer region), the Roman Forum achieved a 0 % PI while AMT achieved a 33.3 % PI and finally during the cooling period the Roman Forum museum achieved a 12 % PI while AMT achieved 40.6 %. These findings establish the last set of criteria by questioning the ASHRAE guidelines. Gennusa demonstrated the difficulty of obtaining suitable indoor environmental parameters in museums when comfort is included in the control criteria. Balancing the guidelines for artwork preservation on display with the thermal comfort of visitors was established as an unattainable task [21]. If the ASHRAE 55-2004 Standard were to be followed, then both museums would need to adjust their environmental controls by the use of HVAC systems, very likely expending additional resources. If priority is given to collections preservation, then underground museums can qualify as potentially sustainable solutions, provided that wider and more relaxed climate control specifications are adopted. This second option would seem to be the more logical as the ASHRAE 55-2004 Standard is oriented towards continuous human occupancy (as in residential contexts), rather than in locations occupied only temporarily, as in the case of museums.

References

[1] UN WCED, A/res/42/187: Report of the World Commission on Environment and Development (United Nations General Assembly 9th Plenary meeting, December 11, 1987), http://www.un.org/documents/ga/res/42/ares42-187.htm (accessed 19 April 2013).

[2] Adams, W.M., The Future of Sustainability: Re-thinking Environment and Development in the Twenty-first Century: Report of the International Union for Conservation of Nature renowned thinkers meeting, (International Union for Conservation of Nature, Gland, 2006), http://cmsdata.iucn.org/downloads/iucn_future_of_sustanability.pdf (accessed 19 April 2013).

[3] International Council of Museums, ICOM Code of Ethics for Museums, (ICOM 21st General Assembly, October 2004), http://icom.museum/fileadmin/user_upload/pdf/Codes/code_ethics2013_eng.pdf (accessed 19 April 2013).

[4] Artigas, D. J., A Comparison of the Efficacy and Costs of Different Approaches to Climate Management in Historic Buildings and Museums, Masters of Science dissertation, University of Pennsylvania (2007) (unpublished).

[5] De Silva, M., and Henderson, J., 'Sustainability in conservation practice', Journal of the Institute of Conservation, 34.1 (2011) 5–15.

[6] Mastrandrea, M.D., and Schneider, S.H., 'Global warming', http://www.nasa.gov/worldbook/global_ warming _worldbook.html (accessed February 2012).

[7] Sterling, L.R., and Godard, J.P., 'Geoengineering considerations in the optimum use of underground space', in An International Conference on Geotechnical & Geological Engineering, Institution of Engineers, Melbourne (2000) 708–720.

[8] Stojić, J., and Stanković, D., 'Bioclimatic underground architecture: development and principles', Architecture and Civil Engineering 8.2 (2009) 135–144.

[9] Kyriakou, V., and Nakhla, A., 'Macedonian tombs microclimatic conditions and problems of their preservation', in 5th International Congress on Restoration of Architectural Heritage, CICOP-UNESCO, Florence (2000).

[10] Kottek, M., Grieser, J., Beck, C., Rudolf, B., and Rubel, F., 'World Map of the Köppen-Geiger climate classification updated', Meteorologische Zeitschrift 15.3 (2006) 259–263.

[11] Corgnati, S., Fabi, V., and Filippi, M., 'A methodology for microclimatic quality evaluation in museums: Application to a temporary exhibit', Building and Environment 44.6 (2009) 1253–1260.

[12] Corgnati, S., and Filippi, M., 'Assessment of thermo-hygrometric quality in museums: Method and in-field application to the 'Duccio di Buoninsegna' exhibition at Santa Maria della Scala (Siena, Italy)', Journal of Cultural Heritage 11.3 (2009) 345–349.

[13] Erhardt, D., Tumosa, C., and Mecklenburg, M., 'Applying science to the question of museum climate', in Museum Microclimates: Contributions to the conference in Copenhagen, 19-23 November 2007, ed., T. Padfield and K. Borchersen, the National Museum of Denmark, Copenhagen (2007) 11–17.

[14] National Museum Directors Conference, 'Guiding principles for reducing museums carbon footprint', http://www.nationalmuseums.org.uk/media/documents/what_we_do_documents/guiding_principles_reducing_carbon_footprint.pdf (accessed July 2012).

[15] Michalski, S., and Grattan, D., 'Environmental Guidelines for Museums - Temperature and Relative Humidity (RH)', http://www.cci-icc.gc.ca/caringfor-prendresoindes/articles/enviro/index-eng.aspx (accessed July 2012).

[16] American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Standard 55-2004: Thermal environmental conditions for human occupancy, ASHRAE, Atlanta (2004).

[17] Olesen, B., Seppanen, O., and Boerstra, A., 'Criteria for the indoor environment for energy performance of buildings: A new European standard', Facilities 24.11/12 (2006) 445–457.

[18] Reilly, J., 'Specifying Storage Environments in Libraries and Archives', in From Gray Areas to Green Areas: Developing Sustainable Practices in Preservation Environments, ed. M. Tedone, Kilgarlin Center for Preservation of the Cultural Record, School of Information, The University of Texas at Austin, Austin (2007).

[19] Michalski, S., 'Quantified Risk Reduction in the Humidity Dilemma', APT Bulletin 27.3 (1996) 25–29.

[20] Reeve, B., Fitzgerald, D., and Kennedy, L., 'Environmental parameters for long-term collection preservation', in Contemporary Collections Conference, Australian Institute for the Conservation of Cultural Material National Conference, October 17–19, Brisbane, ed. A. Pagliarino and G. Osmond, AICCM, Brisbane (2007) 180.

[21] Museums and Galleries Commission, Standards in the Museum Care of Archaeological Collections, http://www.collectionslink.org.uk/media/com_form2content/documents/c1/a79/f6/000072.pdf?phpMyAdmin=OYNyINPdn3sQmoXugKH1gcCLSW0 (accessed July 2012).

[22] Gennusa, M., Lascari, G., Rizzo, G., and Scaccianoce, G., 'Conflicting needs of the thermal indoor environment of museums: In search of a practical compromise', Journal of Cultural Heritage 9 (2008) 125–134.

Author

Dimitrios Karolidis has been a senior conservator at the Archaeological Museum of Thessaloniki since 2006.
Email: dkarolidis@culture.gr

Image credits

Figure 7. Courtesy of Barbara Reeve

Sustainable climate control for art galleries? Experiences at Liverpool's Walker Art Gallery

David Crombie, Chris Bailey, Bernard Connolly, Sonia Jones, Siobhan Watts and Sally Ann Yates

Abstract

The Walker Art Gallery in Liverpool is a traditional art gallery, in a Victorian building that has been modified and extended, with climate control systems ranging from close control air conditioning, to heating without any humidity control. This paper compares the performance of the different climate control systems, and discusses the implications of replacing the unreliable air-conditioning system that controlled two of the eighteenth- and nineteenth- century paintings galleries until recently. Rather than invest significant resources in a replacement air-conditioning system, relative humidity targets were relaxed, and the less energy-intensive approach of portable humidifiers was used for a trial period. Alongside this, a study of heat distribution in the building was undertaken to understand the sources of heat, and the impact of the glazing, lighting systems and other factors. The results have helped us learn more about our building, and have highlighted some simple solutions, such as increasing natural ventilation.

Background
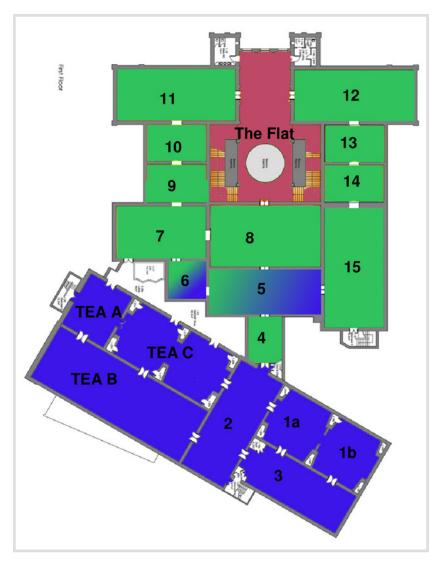
The Walker Art Gallery in Liverpool was established in 1877. The original Victorian design is an impressive neoclassical stone-built civic building, housing collections ranging through fourteenth-century Italian and Netherlandish panel paintings, large Victorian pre-Raphaelite paintings on canvas, to mixed media modern works of art.

Climate control for the collections is provided by different systems, depending on the collections and use of the galleries. Air conditioning with close control of relative humidity (RH) is installed in the temporary exhibition galleries, the early Renaissance galleries, and others with more sensitive panel paintings. Stand-alone portable humidifiers are used, alongside the hot water radiator heating system, for most of the remaining galleries, and the entrance lobby area and stairs have no form of humidity control.

This paper compares the success of different approaches to climate control within the building, with reference to the environmental conditions achieved, running costs and practicalities, and any observed effect on the collections.

Keep it simple and straightforward – the KISS principle

The KISS principle, when applied to design and engineering, states that most systems work best if they are kept simple and straightforward. The original Victorian design of the Walker Art Gallery was arguably a better example of this principle than the

Figure 1. Plan of the first-floor galleries at the Walker Art Gallery, showing the distribution of climate control strategies. Galleries controlled by air conditioning are shown in blue, portable humidifiers are green, and those with no RH control are red. Galleries 5 and 6 were controlled by air conditioning until the beginning of 2011

subsequent twentieth-century interventions. The traditional roof-lights and natural ventilation have been replaced in some galleries by new air-conditioning systems, with the most recent refurbishment in 2001 creating a temporary exhibition suite and close control air conditioning built to host major exhibitions and international loans.

In the twenty-first century, the challenge of continuing to care for the collections in the face of increasing energy prices and budget cuts requires a return to a simpler approach. As the older air-conditioning systems start to fail, the significant resources required to purchase, run and maintain them mean that replacement and upgrading of air conditioning is rarely a feasible option.

The failure of an ageing system in two of the galleries at the Walker Art Gallery in 2010 meant that finding a simpler solution became a necessity. Portable humidifiers were already in use in adjacent galleries, and were frequently used as a standby when the air conditioning failed. The question was asked: are there circumstances in which the simple solution of portable humidifiers can be an alternative to full air conditioning? How do the energy costs compare, and are the savings in installation and energy justified when considered alongside the practicalities of managing humidifiers? What are the risks to collections?

Climate control at the Walker Art Gallery

Figure 1 shows the distribution of different climate control systems on the first floor of the Walker Art Gallery, where the majority of the public galleries are located. Rooms in the 1930s extension to the Walker (galleries 1a, 1b, 2, 3 and temporary exhibition areas A to C) are controlled by air conditioning, including the system installed for the new temporary exhibition suite in 2001, to ensure that it could meet the stringent environmental requirements associated with many loans. Older air-conditioning systems are maintained to serve the Renaissance galleries (1a, 1b, 2 and 3), and it was the older unit serving the eighteenth- and nineteenth-century galleries (5 and 6) that failed in 2010. Other galleries relied on portable humidifiers for control of RH, along with heating set to visitor comfort levels. The central area of the gallery, known as the Flat, is open to the floor below, with staircases on either side. The Flat has no humidity control, but it has secondary heating from pipe-work running under the floor through the area.

Control parameters

The control parameters and strategies for the different systems used until 2010 are listed in table 1. Traditionally the Renaissance galleries had the tightest control of relative humidity, due to the number of potentially sensitive works on panel [1]. The parameters were set in the mid 1980s in accordance with accepted international practice at the time [2].

Air-conditioning failure in galleries 5 and 6

In 2009 and 2010, the air-conditioning system that controlled galleries 5 and 6 became increasingly unreliable, and it was clear that it needed replacing. These galleries contain mixed displays including paintings on panels and canvas, furniture and ceramics.

Table 1. Climate control systems and strategies up to the end of 2010 at the Walker Art Gallery

Gallery no.	Climate control	Age of system	Control parameters
Temporary exhibition areas (TEA) A, B, C	A/C with close control of RH	10 years	Designed with adjustable set point within 40–60 % RH, operated at 50 % RH 19 °C ± 1 °C
1a, 1b, 2	A/C with close control of RH	27 yrs	55 % ± 5 % RH 19 °C ± 1 °C
3	A/C with close control of RH	27 yrs	55 % ± 5 % RH 19 °C ± 1 °C
4	A/C till unit shut down in 2003	18 yrs	similar to gallery 3 when A/C was running
5, 6	A/C with close control of RH	27 yrs	55 % ± 5 % RH 19 °C ± 1 °C
7, 8, 9, 10, 11, 12, 13, 14, 15	Portable humidifiers and hot water radiators	Radiators early twentieth century; humidifiers from 1980s	Humidifiers set to 50 % RH, aim to stay within 40–60 % RH 19 °C ± 1 °C – winter only.
The Flat	Secondary heating, no humidity control		N/A

The air-conditioning problems coincided with initiatives from the UK National Museums Directors' Conference, and the international Bizot Group [3, 4] to broaden parameters for environmental control, and reduce the reliance of art galleries on air-conditioning systems. Given the significant resources required to purchase, run and maintain air conditioning, this provided an opportunity to investigate whether relative humidity targets could be broadened without compromise to collections and to use the less energy-intensive portable humidifiers to maintain conditions.

The air-conditioning unit servicing galleries 5 and 6 was independent of the other air-conditioning systems, and provided heating, cooling, humidification and dehumidification, through full recirculation. The plant did not bring in fresh air, but re-circulated gallery air through a carbon filtration system. Stand-alone, portable humidifiers could obviously only replace one component of the air-conditioning – the humidification. The proposal was to widen the relative humidity parameters from 50 to 60 % (with a set point of 55 % RH), to a stable relative humidity in the range of 40 to 60 % RH, in line with the interim guidelines for hygroscopic materials proposed by the National Museums Directors' Conference in the UK [3].

Analysis of the environmental conditions in other areas of the building suggested that, if the temperature was maintained to visitor comfort levels, increasing the moisture content of the ambient air was the major factor required to bring it within 40 to 60 %. Relative humidity control in the adjacent room, gallery 8, was also provided by portable humidifiers, and in the previous four years the RH measured in gallery 8 did not exceed 60 % at any point. This is primarily because the glazed roof-lights in many galleries result in heat gain in the building in the summer and autumn so that the ambient RH is lower than that recorded in a more typical building. The risk during this time of year was rather that the lack of cooling in the galleries would result in unacceptably high temperatures for visitor comfort.

Other risks with adopting this approach were identified. The first related to the ability to control the temperature to comfort levels in the winter. A programme was set up to switch off different components of the air conditioning in scheduled phases. One of the aims was to identify whether galleries 5 and 6 would require additional heating, or whether the heat transfer from adjacent galleries and thermal inertia of the building would maintain the temperature to within comfort levels. The different components of the air-conditioning unit were switched off in phases: control of humidity was switched off completely at the beginning of January 2011, and three portable humidifiers (two in gallery 5, and one in gallery 6) were set up. Four week test periods were set up to determine the impact of leaving the heating and ventilation off in addition, and operating the system with just ventilation, and with both heating and ventilation on.

The risks identified to collections related to whether the portable humidifiers could maintain a stable RH within the 40 to 60 % range, limiting fluctuations to less than 15 % RH in 24 hours [5]. Research in the previous two decades has suggested that many collections can safely withstand larger fluctuations in relative humidity than previously assumed [6]. However, in galleries 5 and 6 there was a concern that specific paintings had shown previous evidence

of instability and might be adversely affected by either the new parameters set out above or variation beyond them. These included works on both wood panel and canvas.

When considering how to define limits of variations in RH, the maximum of 15 % in 24 hours was adopted, partly as it was felt to be a reasonable figure to compare stability within the 40 to 60 % range, but it also seemed particularly appropriate for the different types of collections on display. A rapid change from 60 % down to 45 %, which then returns to 60 %, may have a different effect on canvas paintings than on panels, since canvas paintings are able to respond more rapidly to changes in relative humidity [7]. The collections displayed in room 5 at the Walker include a significant number of larger works on canvas, many of them glue-paste lined, which may well show a detrimental change in tension during short fluctuations in RH.

There was a further risk relating to the maintenance regime for portable humidifiers. Between 2006 and 2009, the maintenance budgets for stand-alone humidifiers had been significantly reduced, and many had fallen into disrepair. Towards the end of 2009, ongoing problems with the air conditioning highlighted the need for functioning portable humidifiers as a back-up, and funding was allocated to humidifier replacement and maintenance. Developing an effective maintenance programme for the portable humidifiers was clearly an important factor in preventing excessive fluctuations at lower RH, and sustained periods of very dry ambient conditions, which would risk damage to the most susceptible painting in galleries 5 and 6.

Those judged to be at the highest potential risk included five panels in gallery 5 and to a lesser extent, five in gallery 6. The panels in gallery 6 were small and stable, our records showed that none of these had presented evidence of problems in the past, though they may still be at risk from low RH conditions. Of greater concern were two or three panels in gallery 5, including a George Stubbs work that had suffered two previous occurrences of paint loss through movement at a split line in the support. There was also concern for a fragile work on canvas in gallery 6, the Stonebreaker by John Brett, on account of its fragile craquelure.

Evaluating climate control systems
Results from initial test period in galleries 5 and 6

The initial testing period using portable humidifiers was carried out on the basis that if the resulting environmental conditions could not be maintained within the revised parameters (i.e., a stable RH between 40 and 60 %), or were found to be beyond what was acceptable for visitor comfort, then an alternative approach would be needed, e.g., introducing some form of alternative heating and ventilation to the galleries, or even revisiting the replacement of the air-conditioning system.

The relative humidity and temperature charts for the four-month testing period (January to April 2011) for galleries 5 and 6 suggest that in the initial phase the humidifiers were successful at maintaining the RH between 40 and 60 % (Figure 2). The temperature remained within comfort levels (defined as 18 to 25 ºC) for 61 % of the time, generally dropping below 18 ºC when external temperatures were below 7 ºC.
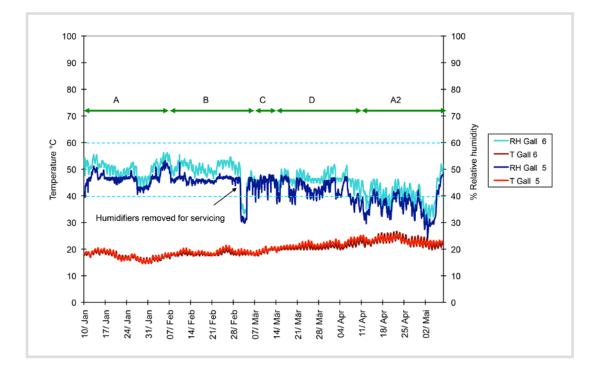
Figure 2. Temperature and Relative humidity in Galleries 5 and 6 during tests to look at effects of switching off components of the air conditioning. Testing periods were as follows: A. 10 January – 7 February, and A2. 11 April – 8 May, all components of air conditioning were switched off; B. 7 February – 7 March, ventilation fans switched on; C. 7–13 March heating switched on with ventilation fans off; D. 14 March – 10 April heating and ventilation fans switched on. The heating in adjacent galleries was on throughout the testing period

The portable humidifiers struggled to maintain the RH in higher gallery temperatures when the heating was switched on, and from mid April, when the UK experienced an unusually warm spring. During this period, the daily fluctuations in RH increased to between 5 and 10 %. The only instance where the RH fluctuations exceeded 15 % was when the humidifiers were removed from the galleries for servicing.

To examine this in a little more detail, the second period during April and May (marked A2 in figure 2) was a repeat of the first test, with all plant shut down in order to try to assess how well the room performed during a period of lower ambient RH. The graph shows that conditions fell below the desired lower parameter of 40 % RH, and conditions were somewhat unstable. However, it transpired that this could not be considered a representative test for a number of reasons. It was an unusually warm spring, as mentioned above, and other factors conspired to exacerbate the conditions. The heating had been left on for longer than usual throughout the rest of the building, which affected galleries 5 and 6 adversely. There were also a number of issues concerning management of the humidifiers during this period, with some units not positioned correctly or developing faults.

It was concluded that period A2 was not representative, but that period A could be interpreted as demonstrating that properly managed portable humidifiers could serve the room well without any of the plant being switched on. It was decided to keep this regime in place and to continue monitoring for a year to assess

results, during which time good humidifier management would be maintained and ways of achieving better temperature control would be examined.

Performance of air-conditioning systems

The question of how to evaluate the performance of air-conditioning systems is significant for this discussion. The general approach at the National Museums Liverpool is primarily responsive: if the parameters fall outside the agreed range, the maintenance engineer is requested to attend. The assessment of galleries 5 and 6 provided an opportunity to look more critically at the performance of different climate control strategies, comparing them year-on-year and, most significantly, trying to understand whether the costs of running and maintaining them can justified, in light of the protection they offer for the collections.

Figure 3 shows the results of one approach to evaluating different climate control systems: the percentage of time for which they maintain the environment within the relative humidity range of 40 to 60 % on an annual basis. For comparative purposes, all the results are evaluated against this broader RH range, rather than the tighter parameters that were within operation for some of the galleries pre-2010.

This illustrates that although the use of portable humidifiers in galleries 5 and 6 resulted in a slight drop in the time that these galleries remained within the 40 to 60 % RH range, their performance in these terms was comparable to other air-conditioned galleries. The results for gallery 8, which was nominally controlled by portable humidifiers throughout the period, indicate the improvement in performance resulting in a dedicated budget for maintenance from 2010 onwards.

These results are a straightforward way to compare the performance of different systems over time, since most environmental monitoring software will automatically calculate these statistics. They do not, however, always give an accurate
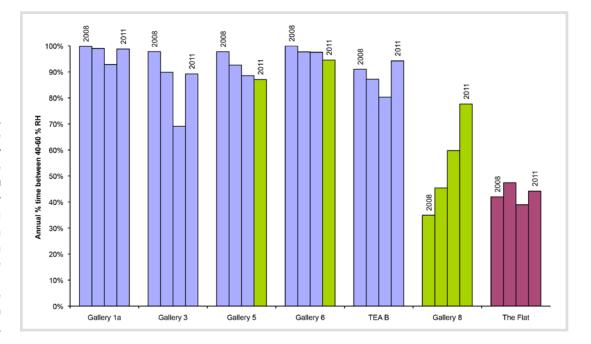
Figure 3. Annual percentage time the gallery environments were within the range 40 to 60 % RH. Colour codes correspond to those used in the gallery plan in Figure 1, i.e., Blue = air conditioned, Green = portable humidifiers, Red = no RH control
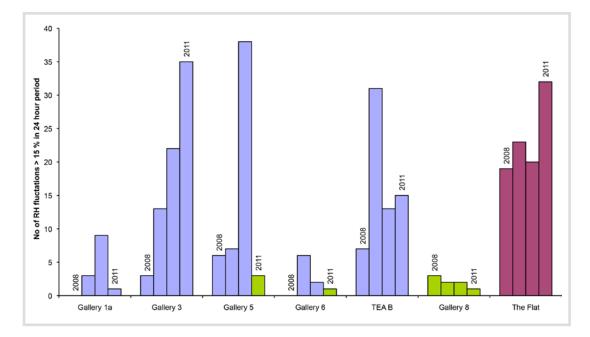
Figure 4. Number of instances in year of RH fluctuations greater than 15 % within a 24-hour period. Colour codes correspond to those used in the gallery plan in Figure 1 i.e., Blue = air conditioned, Green = portable humidifiers, Red = no RH control

indication of the risk to collections, which generally come from either prolonged periods in extremely dry or extremely humid environments, or from large fluctuations in relative humidity. Other more sophisticated approaches have been developed to illustrate and predict the risk that climate fluctuations pose to collections [8]. A simplified approach is to quantify the number of fluctuations in RH greater than 15 %, as presenting a tangible risk. These changes in RH were observed in the monitoring records, and include fluctuations that go either above or below the 40 to 60 % range (e.g., from 46 to 30 %), and those that resulted in a prolonged period of time at a lower or higher RH. This comparison between different environmental control methods is illustrated in figure 4, which compares the different environmental control systems over four years. These results would suggest that a poorly functioning air-conditioning system presents the greatest risk to paintings from fluctuating relative humidity.

The ultimate measurement of performance of a climate control system is the condition of the collections on display, and whether the system is effective in protecting them from damage due to environment. Table 2 lists the numbers of identified works in each gallery where some form of damage can be attributed to environmental effects. The instances of damage are distributed across the different environmental control strategies.

The results in table 2 provide examples that highlight some of the problems with assessing and evaluating damage to collections, in that the cause may not always be identifiable. The problem in gallery 3 in December 2011 when the system circulated air at 90 % RH throughout the room was a straightforward example of a case where a malfunctioning air-conditioning system can have a damaging effect. Condensation formed on picture surfaces, water dripped from the roof and pools of water had to be mopped from the floor. There was no doubt about when the blanching to the picture surface occurred. The control sensors were found to be faulty, and have since been upgraded, resulting in more stable environmental conditions. This is a good example of how fitting new control mechanisms may sometimes allow existing systems to be used more efficiently, if it is decided to keep them in service.

The new flaking observed on the John Brett painting in gallery 6 is not so easy to explain. Between 2010 and July 2012 one area of raised paint was clearly identified as having deteriorated to the point of requiring urgent consolidation. The fragility and potential instability of the work were known and there had been concern about new flaking for some time. It was impossible to say exactly when this change had occurred, or in response to which set of conditions. The span of time between survey points included both the failing air conditioning and the new test regime, so we cannot draw any firm conclusions other than that at some point, variations in conditions brought this about.

More frequent surveys could help this situation, and might make it slightly easier to link changes to certain environmental or other events, assuming these latter are accurately and regularly monitored. In general though, it will rarely be possible to link changes to specific events. As with costs of maintaining equipment, the staff time required to undertake regular and comprehensive surveys may be a resource that is simply not available. Potential problems in some paintings may not become evident for some time after events that may have triggered a certain change, emphasising the importance of a long-term survey programme.

Heat survey of the Walker Art Gallery

Although climate control using air conditioning in art galleries and museums has traditionally been justified in terms of safeguarding the collections on display, the comfort of visitors is another factor that was considered at the Walker Art Gallery. It is easier to provide

Table 2. Environmental effects recorded for collections on display in the Walker Art Gallery

Gallery no.	Climate control	Environmental effects noted on collections
TEA A, B, C	A/C with close control of RH	No events recorded
1a, 1b, 2	A/C with close control of RH	Period of low RH in gallery 2 caused distortion and slight widening of an existing crack to the lid of a piece of wooden furniture
3	A/C with close control of RH	Failure of the system in Dec 2011 resulted in very high RH up to 90 % causing severe blanching to the entire varnish surface of a large sixteenth-century oil on canvas painting
4	A/C till 2003	No events recorded
5, 6 (up to end 2010)	A/C with close control of RH	5: local paint flaking to one eighteenth-century oil on canvas painting – may be an old problem; noticeable corner draws to another canvas painting, not serious.
5, 6 (2011 onwards)	Portable humidifiers	6: New lifting paint on nineteenth-century oil on canvas painting identified July 2012, compared with survey in May 2010; marked variable corner draws to another large oil on canvas painting
7, 8, 9, 10, 11, 12, 13, 14, 15	Portable humidifiers and hot water radiators	New paint run in work from the early 1990s - cause uncertain, possibly relating to temperature fluctuations?
The Flat	Secondary heating, no humidity control	Cracking and flaking of gilded gesso decoration to frame mouldings, probably as a result of very warm dry conditions causing wood frame structures to shrink. Changes in canvas tension noted in several works, with varying corner draws appearing at different times

an alternative method of heating for visitor comfort during the winter than it is to replace the comfort cooling provided by air conditioning during the summer months. The risk of hot, stuffy galleries during the summer months were frequently raised as a concern when switching off the air conditioning in galleries 5 and 6 was discussed.

Figure 5 compares the amount of time annually that the temperatures in air-conditioned and non-air conditioned galleries rose above 25 ºC, from 2008 to 2011. In galleries 1a and 3, the temperature rarely reached this level. However, the warmest galleries were galleries 5 and 6 during 2009; turning off the air conditioning in these galleries in 2011 has not resulted in significantly higher temperatures. It is likely that the higher temperatures in galleries 5 and 6 in 2009 were caused in part by the reheat component in the failing air conditioning operating without adequate cooling capacity to balance it.

Excluding the results from the struggling air conditioning in galleries 5 and 6, the data for room 8 and the Flat indicate that temperatures in the galleries without air conditioning were on average above 25 ºC for more of the time. A heat survey of the galleries without air conditioning was carried out in August 2011 to map the heat distribution across these galleries, identify hotspots, and investigate heat transfer between different areas. An infrared thermometer was used to measure the temperature at defined points on the walls of each gallery, as well as the floors and ceilings. The temperature was measured at set times each morning and afternoon for a four-week period.

Figure 6 illustrates the results, showing the room temperatures in the morning and afternoon, as an average of temperature measured at all four walls, floor and ceiling for each room. The warmer galleries were those in the centre of the building, and on the east side, rather than those clearly facing south. A number of other factors were highlighted as contributing to the heat within the building. Figure 7 illustrates the average floor and ceiling temperatures measured in the galleries. Higher floor temperatures were measured in galleries 4, 5, 6 and 11. Galleries
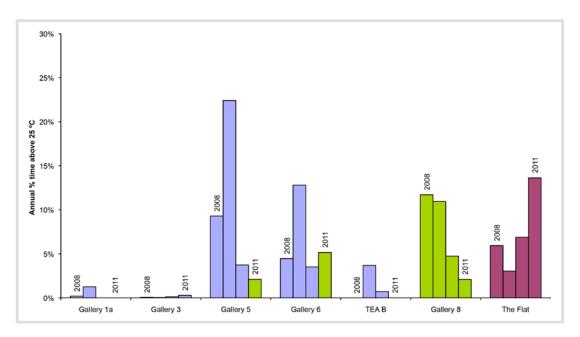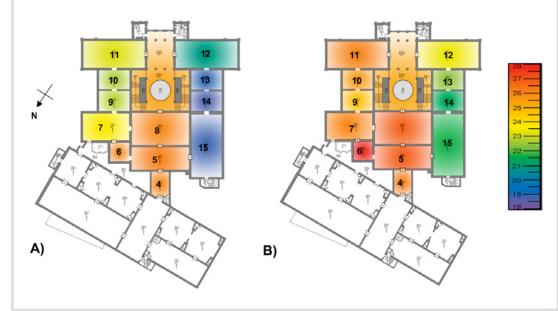
Figure 5. Annual percentage of time the gallery environments were above 25 °C. Colour codes correspond to those used in the gallery plan in Figure 1, i.e., Blue = air conditioned, Green = portable humidifiers, Red = no RH control

5 and 11 were found to have sources of heat immediately beneath them. Gallery 5 is immediately above some parts of the heating, ventilation and air-conditioning plant. Gallery 11 is over the ground floor sculpture gallery lit by 40 halogen spotlights on ceiling-mounted lighting tracks, contributing to the heat transfer to gallery 11 through the floor. Galleries 4 and 6 are both comparatively small so the heat gains within them are not so easily dissipated.

This study suggested some practical options for reducing the heat generated within the galleries. These include increasing ventilation and insulating the ceiling in the area below gallery 5 to prevent heat transfer to the gallery above, and limiting the number of halogen lights in use, or replacing with low-energy alternatives.
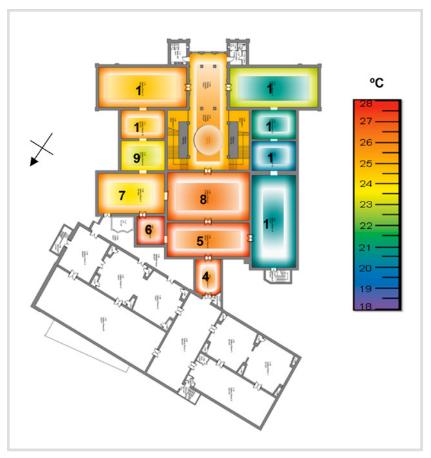
Energy consumption, costs, and practicalities

The use of portable humidifiers to replace the air-conditioning system for two galleries at the Walker is feasible because the central location of these galleries means that the heat from surrounding galleries maintains a comfortable temperature for most of the time during the winter months.

The purchase and maintenance costs of portable humidifiers are relatively low compared to air-conditioning systems: the purchase costs for the humidifiers for galleries 5 and 6 were approximately 6.5 % of the costs of replacing the air-conditioning plant. However, the practicalities of managing portable humidifiers are not always straightforward. They require regular re-filling, so large quantities of water must be carried through the galleries on a daily basis, and staff resources must be allocated to this. Aesthetically, they can look out of place in a historic interior. Managing their cleaning and servicing to ensure that control of relative humidity is maintained can also be a challenge.

The primary cost saving over the longer term by using portable humidifiers is in energy consumption. The energy data for the Walker Art Gallery shows an 8 % drop in electricity use from 2010 to 2011. Comparisons of gas and electricity consumption in the four-week testing phases of heating and ventilation in different

combinations showed that electricity consumption was reduced slightly when the ventilation was switched off. Gas consumption appeared to relate more to seasonal variations than whether the heating for these two galleries was on. The energy consumption was measured for the whole of the Walker Art Gallery, rather than through sub-metering of individual components, so precise attribution of the variations in consumption is not possible.

Conclusion

From the experiences at the Walker Art Gallery, the use of portable humidifiers can potentially give satisfactory results compared to air-conditioning systems, though with some important provisos. If stability of RH is the priority, the environmental data suggests that portable humidifiers can, in some cases, be more effective than air conditioning.

This solution may only be appropriate for galleries 5 and 6 because their location at the centre of the building provides some thermal advantage in winter with the air-conditioning plant turned off. However, methods for improving the maintenance regimes in these galleries must still be examined in order to provide more consistent environmental control. At the Walker Art Gallery, extending this approach to other air-conditioned galleries would require looking at ventilation, heating and cooling as an integrated strategy, for human occupation as much as for the collections. A more detailed study of how the building works would also be needed. The heat survey is a step towards this, and has suggested some practical measures to reduce the heat build up within galleries. There is no doubt that some of the alterations required to address these problems will have their own costs.

The switch to portable humidifiers relies on implementing appropriate management and maintenance regimes to ensure their effectiveness, and this involves considerable staff time. A sustainable approach to collection care requires a system backed up by the maintenance resources to provide stability in the long term. Allocation of suitable resources to a regular programme of collection surveys combined with environmental monitoring may help achieve the best results.

Acknowledgements

References

[1] Michalski, S., 'Incorrect relative humidity', http://www.cci-icc.gc.ca/caringfor-prendresoindes/articles/10agents/chap10-eng.aspx (accessed 17 September 2012).

[2] Thomson, G., The Museum Environment, 2nd edn, Butterworth-Heinemann, London (1986).

[3] National Museums Directors' Conference, 'NMDC guiding principles for reducing museums' carbon footprint', http://www.nationalmuseums.org.uk/media/documents/what_we_do_documents/guiding_principles_reducing_carbon_footprint.pdf (accessed 17 September 2012).

[4] Serota, N., 'Museum environmental conditions in an era of energy constraint', Paper to the Bizot Group Meeting May 2008, http://www.nationalmuseums.org.uk/media/documents/what_we_do_documents/serota_bizot_paper_may08.pdf (accessed 17 September 2012).

[5] British Standards Institution, 'Specification for managing environmental conditions for cultural collections', PAS 198:2012.

[6] Mecklenburg, M., 'Determining the acceptable ranges of relative humidity and temperature in museums and galleries: Part 1, structural response to relative humidity', Smithsonian Conservation Institute, Washington DC (2007). http://hdl.handle.net/10088/7056 (accessed 18 September 2012).

[7] Young, C., and Ackroyd, P., 'The mechanical behaviour and environmental response of paintings to three types of lining treatment', National Gallery Technical Bulletin 22 (2001) 85–104.

[8] Pretzel, B., 'Predicting risks to artefacts from indoor climates', in ICOM Committee for Conservation, 16th Triennial Meeting Preprints, ed. J. Bridgland, Critério, Almada (2011).

Authors

David Crombie is Senior Paintings Conservator for National Museums Liverpool and has worked for NML for 19 years. Email: david.crombie@liverpoolmuseums.org.uk

Chris Bailey is Estates Manager at National Museums Liverpool. Email: chris.bailey@liverpoolmuseums.org.uk

Bernard Connolly is the Mechanical Officer for National Museums Liverpool. Email: bernard.connolly@liverpoolmuseums.org.uk

Sonia Jones joined National Museums Liverpool (NML) as Environmental Officer in 2004. She recently left NML to return to work for the National Trust as House and Collections Manager at Lacock Abbey in Wiltshire. Email: sonia.jones@nationaltrust.org.uk

Siobhan Watts is Head of Conservation Science at National Museums Liverpool. Email: siobhan.watts@liverpoolmuseums.org.uk

Sally Ann Yates was Director of Collections Management at National Museums Liverpool until July 2012.

Image credits

Figures 6 and 7. Illustration produced by Chris Hatter

Solutions for challenging buildings: Storage projects at the Science Museum

Marta Leskard and Louisa Burden

Abstract

The Science Museum Group, a coalition of five museums devoted to the history and contemporary practice of science, medicine, technology, industry and media, has objects stored in a number of leased and fully-owned buildings. Only one of these buildings was purpose-built for museum storage. Environmental conditions within the object stores vary widely.

After taking into account developments in the conservation and scientific understanding of the behaviour of materials and the impetus towards sustainable low-energy solutions for storage, environmental standards were defined for each class of material. Wider bands for both temperature and relative humidity with emphasis on seasonal drift and slow fluctuations from set end points were accepted and the existing storage areas graded for the types of collections they housed.

During a major internal financial review in 2009/10, it was decided to look at the estate held and used for object storage. This developed into a wider collections storage rationalisation project. Reviewing the buildings was only one element of the project; the needs of the collections were closely examined to ensure a well-rounded approach with collections preservation as important as financial savings.

This paper describes two major projects to upgrade existing facilities to accommodate the rationalised reserve collection. It is hoped that the technologies and solutions trialled in these projects can be used again to provide further sustainable storage facilities for the Science Museum Group.

A brief background to the Science Museum Group

The Science Museum Group (SMG) is made up of five museums devoted to the history and contemporary practice of science, medicine, technology, industry and media. SMG incorporates the Science Museum and the Wellcome collections of the history of medicine at South Kensington, the Science Museum Library and Archives at South Kensington and Wroughton, the National Railway Museum (NRM) at York, the National Media Museum (NMeM) at Bradford, Locomotion: the National Railway Museum at Shildon, Concorde 002 with its associated exhibition at Yeovilton, and the Museum of Science and Industry (MOSI) in Manchester.

The Science Museum has its origins in the South Kensington Museum, which was set up soon after the Great Exhibition of 1851. The South Kensington Museum was renamed the Victoria & Albert Museum in 1899 and officially split into the Science Museum and Victoria & Albert Museum in 1909, although they had been operating as two museums for some years before then. The

National Railway Museum opened in 1975 and was established as a result of the transfer of the British Transport Commission's railway collection to the Board of Trustees of the Science Museum. Concorde 002 flew into Yeovilton to become an exhibit at the Fleet Air Arm Museum in 1976. The National Media Museum was established in 1983 with the support of Bradford City Council as part of the council's economic redevelopment programme. Locomotion: the National Railway Museum at Shildon was opened in 2004 in partnership with Sedgefield Borough Council. MOSI was founded in 1969 and joined the Group in February 2012.

SMG storage sites

The storage sites and areas outside the main museum buildings are in a mixture of leased and fully-owned buildings. Only one building out of the whole estate was specifically built as a museum store, all others are converted from other buildings. There have been storage sites at Olympia in west London, Wroughton near Swindon in Wiltshire, Foundry Lane and the Cement Works in York, Black Dyke Mill in Bradford and Brunel Avenue in Salford.

Science Museum storage for small- and medium-sized objects is in Blythe House, west London. Originally built as the Post Office Savings Bank headquarters between 1899 and 1903, the building is shared with the Victoria & Albert and British Museum and is owned by the Department for Culture, Media and Sport (DCMS). Science Museum collections are stored over five floors, in 100 individual rooms.

Large and very large objects are housed on a former military airfield at Wroughton, purchased from the Ministry of Defence in 1979 for use as a collections store. The repurposed airfield, an hour west of London, has objects stored in eight 1930s hangars (four L-type, three D-type and one C-type [1]) and the one purpose-built store, built between 1993 and 1994, spread over the 545-acre site.

The Group owns the NRM site, which was a former steam and diesel locomotive depot just outside the city walls in York, providing considerable floor and rail space. It has a variety of buildings that were converted for museum use. Close to the museum are the Foundry Lane and Cement Works sites which have been used for storage of collections.

NMeM has housed its reserve collections on one floor of a former textile mill, Black Dyke Mill, near Bradford, on a lease basis.

First storage project- Hangar C1

In 2008, an initial investigation was undertaken into the potential for storage of NRM collections at Wroughton as a way of resolving long-term storage issues at York. This was followed in 2009-10 by a major internal financial review to reduce the costs of running the museum group due to the reductions in central government funding caused by the economic downturn. One of the projects within the review was to look at the estate held and used by the group to see where specific savings could be made or income generated. This developed into a wider collections storage rationalisation project. Reviewing the buildings was only one element of the project; the needs of the collections were closely

examined to ensure a well-rounded approach to the project with collections preservation as important as financial savings. Estates and collections departments worked closely together throughout the project.

The collections storage rationalisation project identified that certain stores were particularly expensive to run or required significant investment to bring them up to museum standards for holding collections. In Bradford, space was leased in a shared occupancy building, Black Dyke Mill. This site was difficult for staff to access, security issues were a concern and the general conditions, whilst stable, were not adequate for some of the material in store. At York, the Foundry Lane buildings were in a poor state of repair and had also become inadequate for some of the material stored there. It was also identified that the site could be leased out to external tenants with ease, so generating some much needed income. Wroughton is owned by SMG, with some areas leased out to tenants.

The project objectives and museum collections needs were identified as:

• To review the number of separate stores used within the organisation with a view to reducing overheads;
• To improve the conditions in which some objects were stored: reducing the deterioration of those items currently stored in inadequate environmental conditions;
• To rationalise the collection;
• To allow for new acquisitions;
• To facilitate improved access for collections teams, particularly with regard to selecting objects for future galleries;
• To improve public access through documentation;
• To explore new ways of documenting;
• To open up new loan opportunities;
• To explore possible commercial opportunities;
• To align with other financial review projects.

In April 2010, the then Director of the Group authorised a project to transfer reserve collections from Black Dyke Mill (NMeM) and Foundry Lane (NRM) to Wroughton. It was envisaged that this would reduce the cost of running the estate and increase the number of objects held at Wroughton.

Available storage space was already severely limited at Wroughton and it was evident from the start that a hangar would have to be vacated to provide sufficient space for the objects from the northern stores. As all the hangars were suffering from age and a historic lack of maintenance, whichever was chosen would also need to be refurbished to eliminate problems such as pest and water ingress, hazardous materials, old wiring, poor lighting, blocked or inadequate drainage and structural deterioration such as spalling concrete and corroding ironwork. Limited funding was available for the project as a whole and had to include collections management procedures such as audit and photography, preparation and transport of collections, as well as building renovation in order to fulfil as many of the project objectives as possible.

Initially the hangar chosen for the project was a D-type (cast concrete with bow-strung roof trusses) which had benefited from

some upgrade work in the early 1990s, particularly treatment of the concrete to reduce spalling, improvements to the lighting and wiring, replacement of one hangar door with a rolling shutter door and blocking in of the windows. It would therefore be inexpensive to refurbish. However, this building contained over 60 large objects including three airliners (a Constellation, a DC3 and a Boeing 24D) and it became obvious that it was not logistically feasible to relocate the objects elsewhere on site. The hangar in the worst condition was therefore chosen to be refurbished. This was a C-type steel framework structure with concrete block infill and multi-pitch roof, asbestos-clad with leaking wooden roof, a series of windows, many cracked or broken, along each side and corroding full-height sliding doors at either end, complete with resident populations of nesting pigeons and jackdaws. It also had asbestos-clad and insulated annexes along both sides below the windows. The hangers on site are identified by the hanger type letter followed by a number. The best option available to the museum was identified as renovating C1 rather than refurbishing D4.

A working group of staff from the Science Museum, NRM and NMeM was formed to provide an outline plan with costs to enable stores at York and Bradford to be vacated and hangar C1 to be cleared and renovated.

Conservation and collections care staff at Wroughton audited the other hangars and identified options to relocate the few objects which had been stored in C1; the remaining material in the hangar, including old exhibits material, packing crates, seldom or unused equipment and a substantial amount of rubbish, was either recycled or disposed of.

Estates staff drew up a plan of works for the building renovation based on specifications provided by the working group to produce a building which would securely house approximately 6000 objects from each of the northern museums. Due to funding limitations, it was determined that the building would be wind and waterproof, with limited vapour barrier and insulation. There would be no heating or cooling system and therefore no relative humidity (RH) or temperature controls but fluctuations and excesses of RH and temperature would be moderated to a limited degree by the upgraded building envelope. Neither the chill factor from the concrete floor slab or condensation on the floor would be reduced. Pest entry would definitely be reduced as the hangar doors would be replaced.

Under the SMG collections management storage procedure (which grades storage areas against environmental standards for the types of materials that they house), the improvements would result in hangar C1 becoming a SMG Grade 2 facility, suitable for the storage of robust industrial and transport collections, rather than a low Grade 1, wind and waterproof only building.

Based on environmental monitoring data from the site, with no heating system, RH levels in the winter months could still be higher than 70 % for periods of time. However, even this would be an improvement on at least one of the northern stores, which had a large hole in its roof. Objects stored in the hangar would have to be of robust materials, in good condition or protected by surface treatments, packing materials or other mitigation.

Figure 1. The Science Museum storage site at Wroughton in Wiltshire

Figure 2. Hangar C1 before refurbishment

Figure 3. C1 during refurbishment – hangar doors and annexes removed; steel framework and composite panel cladding being installed

More environmentally susceptible objects for which this was not a suitable environment, even with mitigation, would be stored elsewhere.

After the hangar was cleared, a series of refurbishment works was undertaken. All the asbestos cladding and insulation was removed from the main building and the annexes demolished. The hangar doors were removed and a galvanized steel framework and brick footings were installed in the open spaces to support conventional composite wall panels with an insulated core and some limited vapour barrier properties (Kingspan KS1000RW). The remainder of the hangar was clad with the same composite panels, the windows being completely covered over in the process. Foam filler and butyl rubber sealant were used to close off gaps. The gutters were relined and the drainage upgraded. There were upgrades to the roof panels along the gutter edges but as the roof was considered to be in good condition only repairs identified as necessary were undertaken. No insulation was added to the roof. The interior metal framework and brickwork were sandblasted and painted and the concrete floor given a deep clean. The sodium arc light fittings were replaced by high-intensity halides; fire alarm, intruder alarm and CCTV systems were installed. A vertical rise shutter door replaced the hangar door on the north side; fire exits were installed in the south wall (but no access doors); a double access door was installed on the west side. Because there would be no heating system in C1, a two-room portable office cabin was installed for the use of staff working with the collections; it has heating, a toilet and a small kitchen and data-access points with a PC, printer and the receiver for the Hanwell monitoring system.

To make enough space for the collections being moved from the two northern museums, 14 rows of eight metre high static long span racking were installed; half to accommodate large (1830 x 1370 mm) wooden pallets and half small (1220 x 1020 mm) pallets. Each row was lettered and each bay numbered to pinpoint object locations in the collections database. Access to the objects is via electric reach truck retrieval from the racking with pallet truck handling on the floor. A large space was left at the front of the hangar between the reach truck charging station and the office cabin for object deliveries and study.

C1 refurbishment was completed by June 2011 with the first objects moved from Foundry Lane (NRM) at the beginning of October. By the end September 2012, all the object moves had yet to be completed. An ongoing issue for several months had been leaking from the roof under certain wind directions, though this appears to have been resolved. A lesson learnt from this project

is that, no matter how good it seems, the roof should probably be replaced; it will be cheaper in the long run!

Initially the temperature and relative humidity was monitored in five different places, from floor level to ceiling, using Tinytags, but the data showed that the environment is the same throughout the hangar. Consequently, only one Hanwell monitor has been installed. Data indicated that there has been some minimal moderation of the RH in comparison to external conditions, just as expected. However, C1's environment is now comparable to that inside the all-concrete L1 hangars, which have a much greater thermal mass.

Second storage project – Hemcrete Museum Store (HMS) in hangar D2

The second storage project was initiated in 2010 when financial aid was offered from the Department of Transport to the NRM in order to store the Rail Industry National Archive (RINA). At the time, it was decided that the facility would need to conform to the guidelines of British Standards Institute (BSI) BS5454:2000 [2] as recommended by the National Archives UK. Even though this was subsequently withdrawn by BSI and replaced with PD5454:2012 [3], Guide for the storage and exhibition of archival materials, the engineering design of the building retained the original specifications. About the same time, due to an exhibit development project, three distinct collections of the Science Museum also required conditioned storage, these being the large ship models, the paintings and the horse-drawn carriages. The project was thus extended to include three-dimensional objects.

The storage unit would be built within a D-type hangar; the reserve store for the Science Museum Library and Archive had been built inside half of this hangar some years previously using conventional building techniques with a heating and air-conditioning system. Part of the remaining space would be used for this project.

From information gained through participation in the 2009 workshop on low-energy climate control in museums and archives in Copenhagen (led by Poul Klenz Larsen and Morten Ryhl-Svendsen, National Museum of Denmark and Tim Padfield, consultant in museum climate control), and from ideas generated by a presentation from Mike Lawrence of the Building Research Establishment Centre for Innovative Construction Materials at the Department of Architecture and Civil Engineering at the University of Bath, staff at Wroughton suggested that hemp-lime technology should be investigated as a method of building a more sustainable

low-energy controlled storage building. Lime Technologies (LT), a commercial organisation which produced Hemcrete [MODCELL] [4] as a sustainable building material in the form of modular panels, were asked to provide modelling of a storage facility using environmental data from Wroughton. The modelled results were encouraging. In addition, it was concluded that because modularity to the museum's specification was available both better thermal performance and better climate control were possible. Compatibility with renewable energy sources would potentially lower the operational costs and there was an opportunity for the museum to become an exemplar in the field and work with the University of Bath [BRE] for independent accreditation. LT were contracted to develop a schematic design for the storage units based on criteria for environment, floor-loading, storage furniture, object type, accessibility and space-usage provided by the museum's collections care and archive staff.

ModCell panels are prefabricated and force-dried, and are available in a variety of sizes dependent on use. The panels are timber framed and can be pre-fitted with services; they are made off-site and brought in when required. The panels can be fitted either to timber or steel frames and can be used as roofing material. The hemp in a lime matrix provides extremely efficient hydraulic buffering. Hemp and lime are also natural insecticides and fungicides. The ModCell Panels meet current British Standard fire resistance tests.

A three-level two unit modular building was designed to fill the space right up to the hangar rafters. Although currently the larger unit is intended for the storage of three-dimensional objects, it is possible that future use of the building may be for archival storage so the same floor-loading was used throughout the structure. This meant that the old hangar floor had to be removed and a new concrete floor poured. In an effort to avoid materials with high embodied energy (e.g., concrete planks), Cross Laminated Timber (CLT) [5] planks were proposed for the floors and roof structure. In order to gain maximum effectiveness these planks had to span over the top of the steel beams used in the framework of the building. However, this raised the overall height of the building. As the ground-level ceiling height was chosen to accommodate the tallest of the carriages, the end result was a slightly lower than average ceiling height for the other two levels. Pre-fabricated Hemclad panels were hung from the steel framework. A roller shutter door and an access door were installed for each compartment of the object storage unit; an access door was installed at each level of the archive storage unit; each area on every level also has a fire exit at the rear. Stair access to all levels and the roof was installed at the front and back at the archive end; installation of a lift is planned. Balconies run across the face of the units with reach truck access in front of the doors. In order to prevent rodent access, the outside face of the building was entirely covered in rodent-proof mesh and the decision was taken to neither render nor cover the mesh with fibreboard. The aesthetic appearance of the building was not a priority.

As the approach was to create a building with a stable passive environment as close to the BS5454 conditions as possible, relatively little mechanical and electrical (M&E) input was installed. Two solar photo voltaics-powered air-handling units with heat recovery regulate the internal conditions as required. An

independent Hanwell environmental monitoring system has also been installed as an independent check against the monitoring unit of the mechanical and engineering equipment. It is anticipated that the facility will operate at a third of the running cost and emissions of other SMG storage facilities providing the same environmental standards.

Future projects

The hangers provide storage for the most robust industrial and transport collections but are now of an age where investment is required to ensure long term preservation both of the buildings and contents. This building programme was the first substantial investment in Wroughton's object storage facilities in some years and it is hoped that this will be the start of longer term plans. We are currently working up plans and costings for the refurbishment of an L-type hanger, which we hope can start in this financial year. We also have the possibility of other leased stores in the north of England being closed and new buildings being needed at Wroughton to house those collections.

As we enter the proving period with the Hemcrete store, more information about the environment offered and the sustainability of this facility will be available. We hope that the technology can be used again to provide more object storage for less robust objects and potentially be retrofitted to other storage areas to aid environmental control where the collections require it. Further research work at Wroughton with the University of Bath's Department of Architecture and Civil Engineering is being discussed and the Museum's first conservation-based PhD place has been accepted by the University of Bath, looking into passive building environmental performance for museums.

References

[1] Defence Estates, 'World War II Hangars - guide to hangar identification', Technical Bulletin 02/02, Ministry of Defence (2002).

[2] British Standards Institute, BS 5454:2000 Recommendations for the storage and exhibition of archival documents (2000).

[3] British Standards Institute, D 5454:2012 Guide for the storage and exhibition of archival materials (2012).

[4] ModCell®, The Proving House, 21 Sevier Street, Bristol, BS2 9LB, UK http://www.modcell.com/.

[5] Sutton, A., Black, D., and Walker, P., 'Cross-laminated timber, an introduction to low-impact building materials' http://www.bre. co.uk/filelibrary/pdf/projects/low_impact_materials/IP17_11.pdf (accessed September 2012).

Authors

Marta Leskard has been the Manager, Conservation and Collections Care, at the Science Museum's object store in Wiltshire since 2004. She has recently been offered a place at the University of Bath on the PhD programme in the Department of Civil Engineering. Email: marta.leskard@sciencemuseum.ac.uk

Louisa Burden is Head of Conservation & Collections Care at the Science Museum. Email: louisa.burden@sciencemuseum.ac.uk

Image credits

All images. © The Science Museum

Licence

Learning from history. Historic indoor climate conditions and climate control strategies

Melanie Eibl and Andreas Burmester

Abstract

Recommendations for relative humidity and temperature in museums were initially developed from practical observations on the interaction between works of art and the surrounding environment. Later, the values were specified on the basis of knowledge of the material characteristics of objects and research into the chemical and physical mechanisms of deterioration. The availability of technical equipment to control the environment has also influenced the development of these fixed values, which are today more strict than human comfort criteria.

However, an increased concern to conserve natural resources combined with the financial limitations faced by most museums and historic houses has generated discussion about whether the existing fixed values should be re-evaluated. One of the main arguments is the 'proofed fluctuation concept'. Briefly summarised, the assumption is that if an artwork were damaged by its climate in the past, no new damage will occur as long as the current environmental conditions remain more favourable than the historic extremes. To date, however, this argument has not been proven and there is a lack of research into modelling historic indoor environments.

This paper presents an innovative attempt to reconstruct the 175 years of building history of one of the first free-standing museum buildings, the Alte Pinakothek. Six phases are distinguished, each representing a particular building concept with its own climate control strategy, which impacted in different ways on the indoor climate conditions in the museum. The historic indoor climate conditions and related energy consumption are modelled with input from archival sources such as building plans, blueprints, correspondence, submissions, invoices, etc. By analysing the simulations of past indoor climate conditions, the efficacy of the simple technical interventions of the past is revealed, enabling an insight into the architectural expertise of those involved with the museum over the decades. New information about the historic levels and fluctuations of relative humidity and temperature is uncovered by comparing the different building phases.

This review of past approaches demonstrates that architects in earlier times were generalists who understood the complex interactions between an architectural concept, the building envelope, building physics and the specific conditions of the site. In addition, this retrospective indicates that our construction of the concept of sustainability should also encompass the practice of drawing conclusions from the past for future generations. A sustainable conservation strategy should be based upon an understanding of historic approaches and environmental conditions as well as sound preventive conservation practice informed by social and economic considerations.

Introduction

Attempts have been made to control indoor climate conditions throughout human history. Whereas the early focus was to ensure human survival, as technologies developed the demand for comfort increased. A comparable trajectory can be traced for climate control in museums, in particular for discussions on the correct conditions to be achieved by heating, ventilation and air-conditioning (HVAC) systems. Initially, the recommended levels for relative humidity (RH) and temperature were based on practical observations. Later, an increased awareness of specific material characteristics and a growing understanding of physical and chemical deterioration processes influenced climate recommendations.

Currently, the climate specifications for museums go beyond those required for human comfort. These often lead to the installation of complex HVAC systems to meet the specifications, irrespective of the museum's location, its building envelope or architectural concept. In addition, the high energy consumption of air-conditioning systems is a major financial drain, exacerbated by their operation and maintenance costs.

These problems are combined with an increased awareness of ecological concerns, limited resources and the need to reduce the carbon footprint. This is the background of recent discussions on expanding climate specifications used as set point values to set point ranges. Laboratory experiments on the behaviour of materials under different indoor climate conditions and fluctuations of RH and temperature seem to justify the set point range approach. Furthermore, the argument that objects of cultural heritage have survived despite the fact that historic climate conditions were far removed from today's stringent recommendations often serves as practical evidence for this theory. But what were the historic climate conditions? There is an evident lack of knowledge about historic indoor climate conditions. This contribution aims to reconstruct the 175 years of indoor climate in the Alte Pinakothek in Munich, one of the world's first free-standing picture galleries.

Climate control in museums and museum architecture

Climate set points are defined values for RH and temperature to ensure stable conditions for the preservation of artworks. These often contain hygroscopic materials that react to changes in RH by swelling or shrinking. This phenomenon has been studied over the last 80 years and has resulted in the generally accepted understanding that RH values below 30 % cause embrittlement and shrinkage, whereas values above 70 % cause swelling and mould growth. Specification of absolute values within this range seems to be more a question of belief or of subjective interpretation of real-life observations rather than being founded upon scientifically proven findings. A comparison of the development of set points to developments in HVAC engineering reveals that:

1. Today's set points originated during World War II when objects were evacuated into quarries. This happened in many European countries involved in these conflicts, including England [1], Austria [2] and Germany [3, 4]. In the quarries, a simple heating system was used to keep the environmental conditions constant

at 58 % RH and 17 °C. The fact that no damage occurred was ascribed to the absolute values rather than the extreme stability of the climate.

2. One of the earliest documented set point values was established at the end of the nineteenth century. This was based on pragmatic experience and observations. It is particularly noticeable that human comfort criteria rank lower than achieving the correct conditions to preserve works of art.

3. Historic set points often mirror technical feasibilities of the HVAC systems rather than real preservation requirements. The more powerful the technical installations became, the stricter were the set point values and their ranges of acceptable deviation.

Within the museum world, strict requirements are commonly defined for entire collections, irrespective of the site, the building envelope or the local museum architecture. The relationship between museum architecture and indoor climate conditions is generally ignored. HVAC systems are installed to compensate bad building physics. This dependency not only has ecological and financial implications, but also leaves cultural heritage at increased risk of deterioration [5, 6].

In early museum history, indoor climate conditions were chiefly influenced by the massive building structure. Moisture control meant protection from driving rain and leaky roofs. If there was any heating, this was provided by the combustion of coal or wood. Fresh air was brought into the building by natural ventilation and using the airflow through ducts and chimneys. The only available artificial light sources would have been candles, oil or paraffin lamps, though these were not considered suitable for museums on account of fire risk, heat input and pollutants. Therefore, window openings had to be large enough to ensure sufficient daylight.

During the nineteenth century, two fundamental changes occurred. Central heating systems with radiators were developed, which could distribute hot water or steam from a separate boiler room to every room in the building. Secondly, the first gas lamps offered new possibilities for the illumination of rooms. Although buildings became more air tight, internal and external pollution, mainly caused by combustion processes, increased the need for controlled ventilation. At that time, mechanical ventilation became an urgent challenge. All these factors, ventilation, artificial light and the quality of the building envelope, affected the indoor climate in the past as they do today. As soon as any type of climate control is implemented, set points have to be defined for the operative technicians. The first documented specification of set points for the Alte Pinakothek dates back to the 1880s. Damage of panel paintings caused by the dry air of the installed heating system prompted suggestions that heated rooms should be humidified to around 50 % RH:

'[...] sollen Vorrichtungen angebracht werden, um den Feuchtigkeitsgehalt der Luft in den beheizten Räumen durchschnittlich auf 50 % zu erhalten' [7], which translates into, 'Installations should be placed within the heated rooms to keep the humidity averaged above 50 %'.

But what were the climate conditions in the galleries? And can these historic conditions be linked to the current discussion on set point adaptations?

Climate and building history of the Alte Pinakothek

Increased awareness of the finiteness of natural resources and the financial limitations faced by most museums and collections have prompted discussions on dismissing the existing set point values. One of the recent alternative proposals is the so-called 'proofed fluctuation concept' [8]. Briefly summarised, the assumption is that if climate-induced damage of artworks occurred in the past, no new damage will occur as long as the current climate conditions stay within the range of the historic extremes. But what were the historic extremes and the indoor climate conditions?
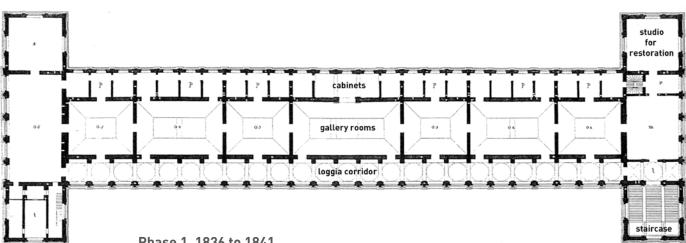
An investigation of the climate and building history of the Alte Pinakothek might offer an initial answer. The general supposition is that every change to this building in the past influenced the indoor climate in some respect. Therefore, the primary goal is to reconstruct the history of the building in order to reconstruct the history of the indoor climate conditions.

The Alte Pinakothek was one of the first free-standing picture galleries in the world. It was built by the architect Leo von Klenze (1784–1864) between 1827 and 1836 for King Ludwig I (1786–1868) in collaboration with 'gallery inspector' Georg von Dillis (1759–1841), its first director. In fact, it was Dillis's 14-point catalogue of requirements, the so-called 'Prememoria' [9] that had the greatest influence on Klenze's architectural design. It is worth mentioning that this building strongly influenced subsequent generations of architects and for many decades became a prototype of museum architecture. The building history of the Alte Pinakothek has been written from an art historian's perspective [10], however there is a lack of information on its technical history.

Information on the 175 years of technical history of the Alte Pinakothek has therefore been collected from documentary sources. These include building plans, blueprints, construction files, correspondence, invoices, and submissions on the construction of the building, its envelope, construction materials, as well as on technical installations and their uses. Its history can be split into six phases of indoor conditions (Table 1).

Table 1. The six different phases of the building and climate history of the Alte Pinakothek

Phase	Period	Short description
1	1836 to 1841	Original building with air-heating planned by Klenze
2	1841 to 1891	Unheated building after deactivation of the air-heating
3	1891 to 1952	Low-pressure steam heating system for heating and humidification
4	1952/57 to 1994	Reconstruction by Döllgast with HVAC for heating and humidification
5	1994/98 to present	Overall refurbishment with installation of a full HVAC system
6	2008/09 to present	Energy-efficient retrofitting of a single gallery room

Labels on plan: studio for restoration / cabinets / gallery rooms / loggia corridor / staircase

Phase 1, 1836 to 1841

In 1836, the gallery opened after a planning and construction period of about ten years. Phase 1 lasted from 1836 to 1841 when the air-heating system installed by Klenze was shut down. At that time, the building was located outside Munich's city wall, which permitted Klenze to place the longitudinal side of the museum in a north-south orientation. Although the gallery quickly acquired the nickname 'Dachauer Gallerie' (being closer to the city of Dachau than to Munich), Klenze's concept of a fully-detached building allowed the galleries to be lit by daylight, minimised the risk of fire, avoided the noise of carriages and also reduced the ingress of dust and dirt.

In total, the building (Figure 1) is 150 metres long with a width of about 50 metres. Both ends have wider front sections which housed the entrance hall, with a huge staircase at the east end and functional rooms at the west. The building has three main levels: the cellar with air-heating ovens placed in so-called 'Klimakammern' (climate chambers), the ground floor, where the print and drawing cabinet, a collection of vases, a vestibule, and storage rooms were located, and the upper floor with eight galleries and 23 cabinets. Above this is an attic crowned by 11 light lanterns in the style of greenhouses, which were constructed by Klenze in response to the problem of daylight illumination under challenging weather conditions (Figure 2). The building envelope is heavy brick masonry faced with yellowish sandstone. The architectural ornamentation consists of green 'Regensburger' sandstone. The roof is covered with sheet copper.

Figure 3 illustrates the tri-partition of the Alte Pinakothek: the major gallery rooms with skylights in the middle of the building, the side-lit cabinets in the north and the abundantly decorated loggia corridor (Figure 6 left) as a passageway and climate buffer in the south. The interior design also reflects the different illumination and uses of the rooms. Whereas the ceilings of the smaller cabinets are flat, those of the large galleries have a special construction. The loggia consists of 25 pendentive cupolas. All ceilings are richly decorated with partly gilded plasterwork. Originally, there were terrazzo floors in the whole building, except for the vestibule that had tiles and the grand staircases that were made of marble.

Klenze argued that a heating system was required for the preservation of the pictures and for visitors' comfort [11]. Being aware of the fire risk caused by any heating system, he planned

14 masonry niches in the cellar in which he placed the wood-fired air-heating ovens. Fresh air, as well as heated and exhaust air, was channelled through brick ducts placed in the walls of the building which were about one metre thick. In the gallery rooms themselves, warm air was supplied through vents directly below or next to the paintings. The exhaust air was extracted about 15 to 20 cm above the floor. The smoke ducts were also routed through the massive walls to chimneys on the roof. Natural ventilation was provided by leakage through the building envelope, air exchange between the different rooms and by opening the windows manually.

Phase 2, 1841 to 1891

Within a few years of opening, the air-heating system was acknowledged to be a failure. In 1841, the system was switched off due to severe damage observed on many of the gallery's paintings. In particular, large temperature fluctuations had caused even larger fluctuations in RH, and there were dust and dirt accumulations on painting surfaces:

'Man hatte sich nämlich überzeugt, daß die am höchsten hängenden Bilder dann, wenn die unteren in einer angemessenen Temperatur – etwa 12–15 ° Celsius – sich befanden, einer höchst nachtheiligen Hitze ausgesetzt waren, und daß die durch die Heizluft mitgeführten Staubmengen außerordentlich schädlich auf die Bilder einwirkten' [12], which translates into, 'It was obvious that the highest placed pictures on the wall suffered from an enormous heat whereas the lower placed pictures found themselves in an adequate temperature of 12 to 15 °C and that the dust transported by the heated air is extremely harmful to the paintings'.

For preservation reasons, the galleries were not heated from 1841 to 1891. Abandoning the heating led to room temperatures as low as -5 °C during winter, which resulted in blooming on painting surfaces and mould growth. Furthermore, the building and its installations had also suffered damage. During phase 2, maintenance and housekeeping was not carried out due to a lack of financial support from the Bavarian state.

Figure 2. Klenze's light lanterns on the roof of the building in 1938
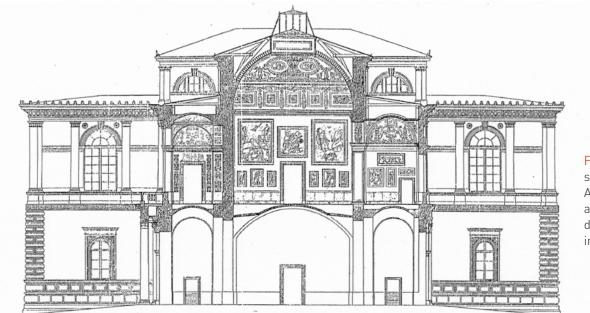
Phase 3, 1891 to 1945

The poor condition of the galleries finally led to a major renovation in the late nineteenth century. This included the installation of a new heating system: a low-pressure steam heating system was employed not only to heat the galleries but also to humidify them to some extent. The gallery floors were covered with oak parquet to replace the former terrazzo floors. The walls were given a new textile covering, and the copper cover of the light lanterns was replaced by depolished glass. About 20 years before the new heating system was put into operation, a commission of experts evaluated existing climate control systems in the most prominent European museums in order to devise a climate control concept for the Alte Pinakothek. Their report included a description of the advantages and disadvantages of the inspected systems as well as one of the first recorded remarks on set point values for museums:

'Bei der Aufstellung des Programmes war als Hauptforderung vorangestellt, daß die Heizung nicht durch unzweckmäßige Temperatur oder unrichtigen Feuchtigkeitsgehalt der Luft die Bilder schädige, sondern möglichst zur Erhaltung derselben mitwirke und erst in zweiter Linie, daß sie den Malern, Beamten und Bediensteten den Aufenthalt angenehm mache [...] oder mit anderen Worten, es soll der Feuchtigkeitsgehalt der Luft fortwährend so nahe als möglich auf 50 Prozent Sättigung erhalten werden' [12], which translates into, 'On developing the programme, the main request was that the heating should cause no harm to painting due to inappropriate temperature or incorrect humidity of the air. In the first instance, the heating should contribute to the preservation of the pictures and only after that fulfil human requests for comfort [...] or in other words, the humidity level of the air should be permanently kept close to 50 % saturation'.

As clearly stated, the conditions for the paintings had priority over human comfort. The final heating system consisted of four wrought-iron low-pressure steam boilers located in the cellar. These supplied steam to the c. 110 ribbed radiators in the building. In the cabinets, the radiators were placed in the window recesses. In the galleries, the radiators were integrated into 13 so-called 'Divans', which were large pieces of upholstered furniture in the middle of the rooms. Inside these 'Divans', water basins were

placed above the heating pipes to humidify the air by evaporation (Figure 4). The room climate was measured to optimise control of the indoor conditions and in response to past bad experience. The documentation includes an accurate register of the annual combustible material consumption, daily notes on water usage for evaporation, and records of daily RH and temperature measurements. The data indicate that during winter temperatures of about 12 °C were achieved with this system. During the heating period, up to 250 litres of water per day were evaporated to increase the RH in the galleries.

Phase 4, 1957 to 1994

From 1939 onwards, large parts of the collections were evacuated, and the building was severely damaged by Allied bombs in 1942 and 1944 (Figure 5). Reconstruction of the building by the architect Hans Döllgast (1891–1974) led to a massive alteration to Klenze's original architectural and technical concept.

The controversial reconstruction campaign lasted until 1957, when the museum re-opened. Reconstruction was conducted in three stages. It began in 1952 with removal of debris, safeguarding of the roof and the bare brickwork. Döllgast treated the building's 'wounds' as a kind of memorial by leaving them openly visible. The interior fitting started in 1955, which again led to major changes in the original concept: the former main entrance on the east side was relocated to the north side in the centre of the building. The loggia corridor along the main galleries, which had been almost completely destroyed, was not reconstructed. Instead, it was turned into a hughe staircase connecting the entrance hall with the first floor galleries on both sides (Figures 6 and 7). The light lanterns were not rebuilt, but larger areas of the roof were glazed. In line with the reconstruction work, a simple air-conditioning system was installed which allowed the air to be heated and humidified. Cooling and dehumidification were not possible at that time. This led to high temperature and high RH in the

galleries during the summer, which caused frequent complaints from visitors and security staff. The whole building was supplied with heat from various systems; the new entrance hall (former vestibule), for example, had floor heating. Only the galleries were completely air-conditioned at a RH of 60 % and a temperature of 20 °C as minimum levels. However, the aerosol devices used for humidification of the warm air caused a substantial electrostatic charge of dust accumulating on the painting surfaces. For the first time in the history of the Alte Pinakothek, artificial lighting was installed. Indirect illumination of the galleries was achieved by c. 900 fluorescent tubes with 64 and 40 watts attached in triple rows to the cornice below the haunches. Furthermore, 16 electric bulbs with 300 watts were also installed for cleaning purposes [13].

Phase 5, 1994 to present

The disadvantages of the air-conditioning system of the 1950s required a general refurbishment of the building between 1994 and 1998. Although the architectural concept of Döllgast's reconstruction was not touched in principle, a full HVAC system was installed. From now on, the air could be heated, cooled, humidified and dehumidified using 49 decentralised units supplying the gallery rooms, the depositories and the conservation studio. The air exchange rate is three to four times per hour. Depending on the outdoor conditions, the fresh air rate in the galleries is about 10 %. The lighting system now consists of 1,543 fluorescent tubes with 36, 58 and 72 watts, mirror reflectors and prismatic diffusors. The illumination concept combines artificial light and daylight. A curtain system was installed in the attic to regulate incident daylight. The single glazing in the skylights was replaced by double glazing with UV filters. However, due to serious planning failures, the mechanical shading system had to be turned off some months after re-opening. To avoid high illumination levels, large textile sheets were permanently fitted to the skylights.

Figure 5. Bomb damage of the Alte Pinakothek in 1945

Figure 6. Loggia corridor around 1930 (left) and today's staircase (right)

Phase 6, 2008 to present

The insufficient lighting concept and, above all, the low energy efficiency of the attic, recently prompted an exemplary refurbishment of one of the galleries (Gallery X). An overall concept for the energy-efficient retrofitting of the whole building has been developed on the basis of Gallery X; however, this has not yet been put into practice. In Gallery X, the first stage was internal insulation of the roof using a layer of 15 cm mineral wool, a vapour barrier and plasterboard. For the new glazing of the roof lights, a combined sun-protecting and heat-reflecting glass with a colour rendering index of 95 % was chosen. The skylights were fitted with a light diffusing prism glass with a transmittance of 70 %. To control incident daylight, a louvre system was installed in the attic. It is regulated according to the seasonal solar zenith angle. The artificial light installations in Gallery X were transferred into the attic. They consist of fluorescent tubes and four floodlights; however, this solution will not be used in the future due to its high energy consumption.

Historic indoor climate conditions and energy flows
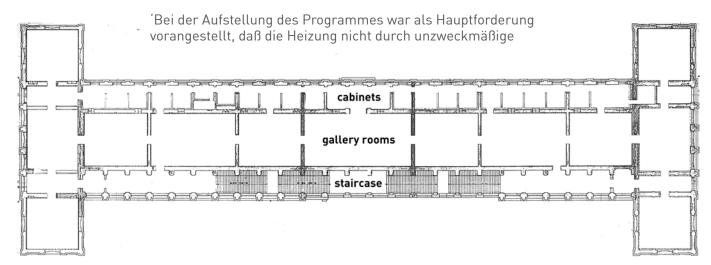
The parameters of phases 1 to 6 and additional information were used as input data in a hygrothermal building simulation [14]. The simulation of the six building phases aims to provide an initial picture of the historic conditions, namely RH and temperature as well as the particular energy flows of phases 1 to 4. Although the absolute values were not the main focus, the simulations allowed the conditions of the six phases to be qualified and compared. The central exhibition room (Rubens Gallery VII) was of most interest, and a cross-section through the whole building was modelled.

Scatter plots were used to facilitate comparisons of the simulation results for RH and temperature. These plots include all the information for phases 1 to 6 over a period of one year (Figure 8). A detailed description of the complex simulation process can be found in the masters thesis of one of the authors [9].

Not unexpectedly, every phase shows a characteristic distribution of RH and temperature. In contrast to phase 4, there were no technical measures to control the indoor climate between April and October during phases 1 to 3, in which the building's envelope was the determining factor. Here, the massive masonry was responsible for the delayed but moderate influence of the outdoor climate on the indoor conditions. During phase 4, the indoor climate conditions were kept above a temperature of 20 °C and 50 % RH throughout the year. The main differences between phases 1 to 3 can be observed in the winter months, i.e., during the heating period between November and March. There was no temperature control at all during phase 2, and the indoor climate was characterised by low temperatures and high humidity. The air-heating system of phase 2 was used to raise the temperature levels. However, serious humidity drops occurred. As we know, such drops provoked severe damage to the paintings on display. In consequence, the system was switched off. The low-pressure steam heating system was the first attempt to raise the temperature level and to humidify the air simultaneously. A comparison of phases 1 to 3 reveals the important finding that the temperature was not controlled for the sake of visitors but to keep the building above freezing. Preservation of the artworks was the main concern, or, as formulated by the commission in charge:

'Die Kommission machte deshalb in ihrem Berichte auf die Bedeutung einer guten Heizung aufmerksam, indem sie hervorhob, daß in jeder Galerie die Temperaturverhältnisse so weit zu regulieren seien, daß es nie zur Taubildung oder zu feuchten Niederschlägen auf den Bildern kommen könne' [12], which translates into, 'The commission pointed out the significance of sufficient heating in its report, by emphasising that the temperature in every gallery has to be regulated in a way that condensation or wet deposits never occur on the paintings'.

Due to Klenze's knowledge about conservation needs and about the technical limitations of his time, his main intention was to keep the building above freezing. The tenor during the planning of the low-pressure steam heating system for phase 3 was quite different:
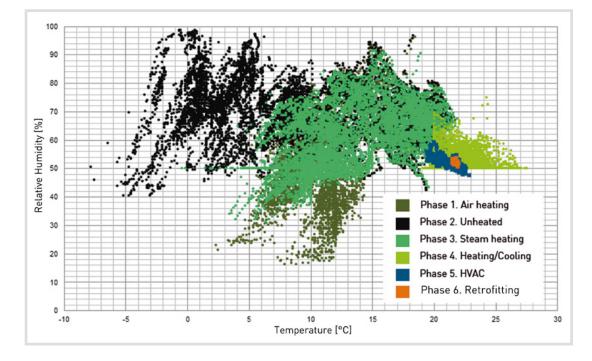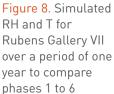
'Bei der Aufstellung des Programmes war als Hauptforderung vorangestellt, daß die Heizung nicht durch unzweckmäßige

Figure 7. Ground plan of the Alte Pinakothek after reconstruction in 1957

Temperatur oder unrichtigen Feuchtigkeitsgehalt der Luft die Bilder schädige, sondern möglichst zur Erhaltung derselben mitwirke und erst in zweiter Linie, daß sie den Malern, Beamten und Bediensteten den Aufenthalt angenehm mache. [...] Der Aufenthalt bei der jetzt eingehaltenen Temperatur ist ein ganz erträglicher, und es wäre deshalb ungerechtfertigt, nur um den Besuchern noch etwas größere Bequemlichkeit zu bieten, der Gefahr sich auszusetzen, daß bei nicht vollkommen aufmerksamer Bedienung eine Schädigung der Bilder entstehen könnte' [12], which translates into, 'The primary intent of the concept was that the heating should not harm the paintings by leading to insufficient temperature or incorrect humidity of the air but should contribute to their preservation. And of minor intent it should provide a comfortable stay for painters, officials and employees. [...] The recently achieved temperature is tolerable for visitors and therefore it would be unjustified to face the risk of damages caused by insufficient handling just to offer them a little more comfort'.

The commission's experts understood that RH is an important factor for the preservation of artworks, and that temperature control alone was not sufficient. Moreover, they denied a further raise in temperature simply for human comfort, because this was associated with higher risks for the whole collection as well as drastic increases in energy consumption.

According to international standards, the air-conditioning system of phase 4 led to a temperature of 20 °C and prevented the RH dropping below 50 %. However, the indoor climate showed fluctuations of about 25 % in RH and about 10 K in temperature.

A detailed analysis of the fluctuations in phases 1 to 6 is shown in table 2. It is obvious that the range of annual RH fluctuations became smaller from phase to phase. During phase 1, there is a deviation from the annual mean RH of about 40 %. Heating during phase 1 narrowed the band of annual temperature fluctuations, whereas the highest annual fluctuation in temperature occurred during phase 2, when the building was not heated at all. During

Figure 8. Simulated RH and T for Rubens Gallery VII over a period of one year to compare phases 1 to 6

Phase	Deviation from annual mean		Daily fluctuations winter		Daily fluctuations summer	
	Δ RH [%]	Δ T [K]	Δ RH [%]	Δ T [K]	Δ RH [%]	Δ T [K]
1	< 40	< 9	< 10	< 5	< 5	< 1
2	< 32	< 15	< 7	< 1	< 5	< 1
3	< 26	< 11	< 10	< 2	< 5	< 1
4	< 12	< 5	< 2	< 1	< 5	< 4
5	< 5	< 2	< 2	< 1	< 2	< 1
6	< 4	< 0.5	< 1	< 0.5	< 1	< 0.5
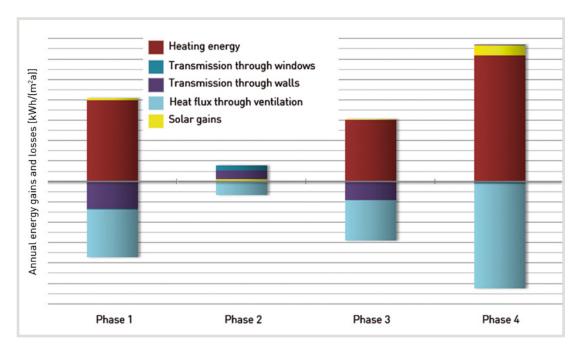
phases 1 to 3, the summer conditions seemed to have been fairly stable, whereas the highest daily RH fluctuations occurred during winter in phases 1 and 3. The reason why phase 2 shows lower fluctuations in temperature is the fact that the galleries were heated during the day during phases 1 and 3. Introduction of an air-conditioning system during phase 4 reduced the annual fluctuations. The daily fluctuations during winter were no longer of great relevance. In summer, the enlarged areas of glazed roof and the lack of cooling led to raised daily fluctuations in temperature. With the introduction of the full HVAC system in phase 5, the temperature and RH fluctuations could be minimised year round. A comparison of phases 5 and 6 shows that sufficient insulation of the roof and improved glazing achieved a further stabilisation of the indoor climate. This substantial improvement was reached without any changes to the air-conditioning system or the set point values for RH and temperature.
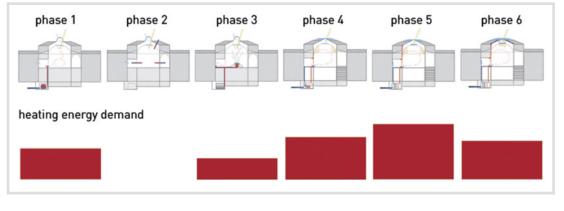
Figure 9 visualises the energy gains and losses for Gallery VII during phases 1 to 4. The bars represent the annual sums of monthly energy gains and losses, such as heating demand, transmission through windows and opaque elements, solar gains and heat losses due to ventilation or leakiness. As expected, energy flows are at the lowest level during phase 2, in which gains and losses are determined by the outdoor climate and the influence of the building envelope. If heating is added, the energy losses through transmission and ventilation increase. Phase 1 and 3 are comparable because the heating periods coincide. The explanation of why the heating demand for the low-pressure steam heating system (phase 3) was less than for the air-heating system (phase 1) lies in the fact that air is generally a good insulator and therefore is not particularly suitable for climate control purposes. The insulated water pipes of the low-pressure steam heating system are obviously more efficient. The doubling in heat demand from phase 3 to 4 can be explained by the increase in the temperature set point from about 13 °C to 20 °C and by the fact that during phase 4 there was no longer a heating period: the heating was turned on all year round. Every time the temperature dropped below the set point, heating energy was requested. Not surprisingly, the solar gains increased with enlargement of the glazed areas, such as the skylights which were doubled in size.

Conclusion

A simulation of the different phases in the building history of the Alte Pinakothek reveals that modifications to the building envelope or interventions in the climate control strategy have always influenced the indoor climate conditions. A comparison of the six investigated phases leads to an obvious conclusion: since the 1950s, the set points for RH and temperature have closely followed improvements of technical equipment for environmental control (Figure 10). The resulting uncontrolled increase in energy demand is now a double burden because both the financial considerations and the increased carbon footprint necessitate sustainable interventions. Simply changing the set point values for RH and T, as recently proposed by the Bizot group, is not a sustainable intervention. Lower energy consumption and an essentially stable indoor climate can be achieved through other means, as demonstrated in phase 3. To develop further successful approaches for the future, any museum building must be understood as a holistic system within its particular location. It has specific needs for its collections and the building envelope. Why not learn from the past and use historic concepts adapted with modern materials to meet present-day requirements?

The Alte Pinakothek and its rich collections are an excellent example of such a holistic approach. Over most of its 175

Figure 9. Annual energy gains and losses for Rubens Gallery VII during phases 1 to 4
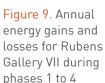
Figure 10. Comparison of the heating energy demand for Rubens Gallery VII during phases 1 to 6.

years, the building has provided improved conditions for the preservation of its collections. This among others is a reason why this museum building has such a great impact on following generations of museums. Its patron, Ludwig I of Bavaria, forced an interdisciplinary exchange between the architect Klenze and the museum director Dillis. Today, we would say that the museum's concept has been developed by a multidisciplinary team of architects, engineers and conservation professionals. Finally, learning from history is also an aspect of sustainability. Drawing conclusions from the past for tomorrow means implementing lessons learnt by earlier generations while considering the environmental, social and economic challenges for future generations that will arise from present-day decisions.

References

[1] Bosman, S., 'The gallery in war time', http://www.nationalgallery.org.uk/paintings/history/the-gallery-in-wartime/ (accessed 19 April 2013).

[2] Frodl-Kraft, E., Gefährdetes Erbe. Österreichs Denkmalschutz und Denkmalpflege 1918–1945 im Prisma der Zeitgeschichte, Vienna (1997) 339 and 512–515.

[3] Schawe, M., Vor 50 Jahren – Die Bayerischen Staatsgemäldesammlungen im Zweiten Weltkrieg, in Bayerische Staatsgemäldesammlungen, Annual Report (1994) 9–27.

[4] Schawe, M.,1947 – Die Bayerischen Staatsgemäldesammlungen, in Kunstgeschichte in München 1947. Institutionen und Personen im Wiederaufbau, ed. I. Lauterbach, Zentralinstitut für Kunstgeschichte, München (2010) 91–104.

[5] Burmester, A., 'Modern museums: the architect's triumph, the conservator's nightmare?', Studies in Conservation 48 (2003) 210–214.

[6] Burmester, A., 'Visions for a new museum: the museum Brandhorst (Forbes Prize lecture)', Studies in Conservation 50 (2005) 69–75.

[7] Bayerische Staatsgemäldesammlungen München (BStGS). Registry file 16/3 No. 314 73.

[8] ASHRAE, 'Chapter 21 Museums, Galleries, Archives and Libraries', in ASHRAE Handbook – HVAC Applications, ed. M.S. Owen, American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc., Atlanta (2007) 21.2–1.23.

[9] Eibl, M., Lernen aus der Geschichte. Historisches Klima in Museen und resultierende Klimatisierungsstrategien am Beispiel der Alten Pinakothek, Masters thesis, Technical University, Munich (2011) (unpublished) 36.

[10] Böttger, P., Die Alte Pinakothek in München Architektur, Ausstattung und museales Programm, Prestel-Verlag, München (1972).

[11] Klenze von, L., Sammlung architektonischer Entwürfe, welche ausgeführt oder für die Ausführung entworfen wurden, Heft 1, Munich (1930) 3.

[12] BStGS registry file 16/3 No. 314, newspaper article, Zweites Morgenblatt 31 (1892).

[13] Staatsarchiv München LBÄ 2114, Cost estimate for the new arrangement of the Alte Pinakothek from 21 June 1956.

[14] Eibl, M., Lernen aus der Geschichte. Historisches Klima in Museen und resultierende Klimatisierungsstrategien am Beispiel der Alten Pinakothek, Masters thesis, Technical University, Munich (2011) (unpublished) 99–183.

Authors

Melanie Eibl is responsible for preventive conservation at the Doerner Institut. She is also undertaking a doctoral degree in preventive conservation and museum architecture. Email: eibl@ doernerinstitut.de

Andreas Burmester is the director of the Doerner Institut. He is also a professor at the Technical University in Munich. His main interests are pigment history, primary sources and preventive conservation. Email: burmester@doernerinstitut.de

Image credits

Figures 1, 2, 4, 5, 6, 7. © Bayerische Staatsgemäldesammlungen
Figure 3. Klenze, Leo von: Sammlung architektonischer Entwürfe, München 1831
Figures 8, 9, 10. © Melanie Eibl

Licence

From artwork to building preservation. Some considerations on the 'historical' indoor climate of Villa Reale in Milan

Andrea Luciani, Carlo Manfredi, Davide Del Curto and Luca P. Valisi

Abstract

Analysing the indoor climate of historic buildings is very complicated, involving different variables and uncertainties. This paper presents some reflections about an interesting case study, the eighteenth-century Villa Reale in Milan, which holds the civic collection of modern art. A nineteenth-century air heating system operates in the museum, generating an unsuitable indoor climate that presents risks to the collections and is not comfortable for users of the building. A research project was established by the Politecnico di Milano to examine environmental control in the museum.

The assessment of existing conditions was based on an extended application of the concept of historical climate, an integrated approach which is particularly significant in this case study. Results from the monitoring and surveying activities are presented, focusing on the relationship of the building construction with the indoor and outdoor climate as well as on potential deterioration factors for the collection. Outcomes, uncertainties and methodological questions generated by the research are also discussed.

Introduction

Since 1921 the Gallery of Modern Art in Milan has been housed in a building originally designed by the architect Leopoldo Pollack as a private dwelling. The villa was built in 1790 for Earl Ludovico di Belgiojoso at the end of his long career as an officer and diplomat. The architect was inspired by the criteria of **distribution**, as defined during the eighteenth century. Following the treatises edited by Briseux, D'Aviler or Jacques-François Blondel [1], which reflected on the modern development of the **intérieur**, the interiors of the villa were designed to provide comfort features that went beyond creating a pleasant environment. This type of architecture was intimately tied to the ritual and protocol of the court, particularly in France, where the project of the Petit Trianon by Anges-Jacques Gabriel for Madame de Pompadour was probably the most significant example. The model originating with these **Maisons de Plaisance** (the title of the most popular treatise by Blondel) became quite common in many upper-and upper-middle class European dwellings. The influence of the model transcended its original political connotations and prevailed despite the revolution that swept away the Ancien Régime.

The model influenced the Earl Belgiojoso, who wanted a building with state apartments, reception salons nd a suite of rooms in double apartments overlooking the garden as well as cutting-edge facilities, including spacious kitchens and lieux à l'anglaise. Behind the apparent regularity of its architecture, the villa was designed to separate the service areas from living areas by means of corridors
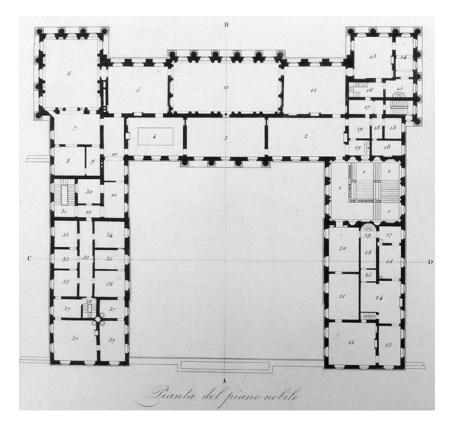
Pianta del piano nobile

and secret staircases. For example, Pollack designed large stoves, some which were made of masonry, to be supplied from corridors. To counteract the mild winters of Milan, the architect arranged the orientation of the villa so that halls and rooms were facing to the south and west.

Following the death of Ludovico Belgiojoso, the building was purchased in 1803 by the newly formed Napoleonic Italian Republic and soon became the residence of Prince Eugène de Beauharnais, Viceroy of the Kingdom of Italy, who lived there until 1814. The name Villa Reale, still in use today, dates back to this short period. The villa was used by the Habsburgs as a state residence during the Restoration. After 1860, under the House of Savoy, it became an asset of the Crown of Italy and in 1921 was transferred to the Italian State.

Several refurbishments of the interior were undertaken during the 1860s. A central heating system with ovens **à la Meissner** was installed to heat the main body of the building, which overlooks the garden. It was a rather simple scheme, devised in the 1820s by Paul Traugott Meissner, and disseminated in many technical treatises of the nineteenth century [2]. The most likely reference for the system at Villa Reale is the third edition of the **Traité de la Chaleur** by Péclet [3]. It was essentially a **caloriphère à air** consisting of underground ducts that drew in external air and large ovens in the basement that heated the air, which was then distributed by a system of vertical ducts built into the thickness of the walls. There were six ovens (five of them remain) to heat nine rooms. The ovens were equipped with iron stoves, fuelled originally by wood then later by coal. At some point, probably around the beginning of the twentieth century, the stoves were substituted for heat batteries composed of finned tube. Today, hot water is supplied from an external boiler through a circuit of pipes. Warm air is distributed by natural convection without any mechanical

system. The air-heating system operates in the main body of the building, while the wings are heated by radiators, mostly installed at the beginning of the twentieth century. The same pipe circuit supplies the hot water to both systems. While the regulation of a modern plant is based on controlling the air temperature and flow, here only the water temperature of the feed pipe can be regulated.

The villa has been used as a museum since 1921 and hosts the civic collection of modern art, mainly sculptures and paintings (mostly on canvas). As in many other European countries, formerly privately-owned buildings have assumed public functions. The re-use of the villa as a museum has not always been considered well suited to the particular features of the building. Criticism has focused on the dissonance between the architectural style and decorative features (mainly of the early nineteenth century), and the modern nature of the museum collections. Even commentators interested in architecture considered the rich interiors of the villa unsuited to housing the current Gallery of Modern Art [4].

Beyond these aesthetic questions, the condition of the collection has become an increasing concern, particularly in terms of the
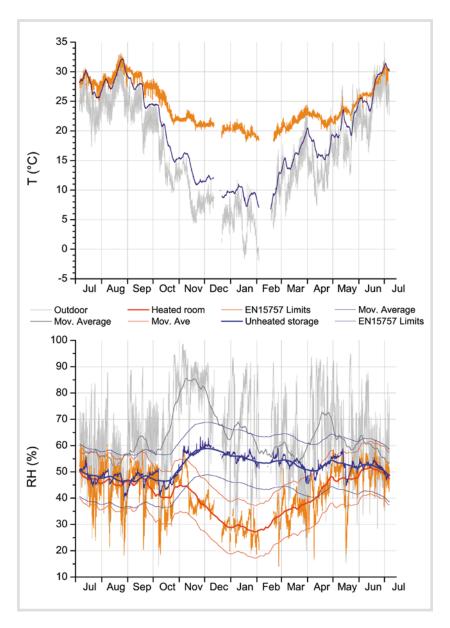
Figure 2. Yearly trends of T and RH in Room VII (orange) and in the storage area (blue)

possible relationship between deterioration and the internal environment. Specifically, some nineteenth- and early twentieth-century paintings started to present craquelure and detaching paint layers. A recent problematic retrofitting of the heating system has exacerbated the situation. In addition, the environmental conditions are not comfortable for visitors and museum staff, particularly in the summer.

Conservators have expressed concern about the potential connection between the deteriorating condition of the collection artworks and the indoor climate. The aims of the current research are to understand how the building and heating systems affect the indoor environment and to identify the related risk factors for the collection. The results of two years of monitoring and analysis are discussed in this paper.

Method and approach

The indoor climate was assessed with reference to the building envelope, internal museum activities and existing heating systems. The final part of the exercise was to propose solutions to improve the poor environmental conditions.

When considering future interventions, it was clear that the old heating system should be valued as rare material evidence of a historic technology. Another basic requirement was that the impact on the existing building should be minimal. It was evident how difficult it would be to create an environment that complied with traditional hygrothermal specifications within these limitations.
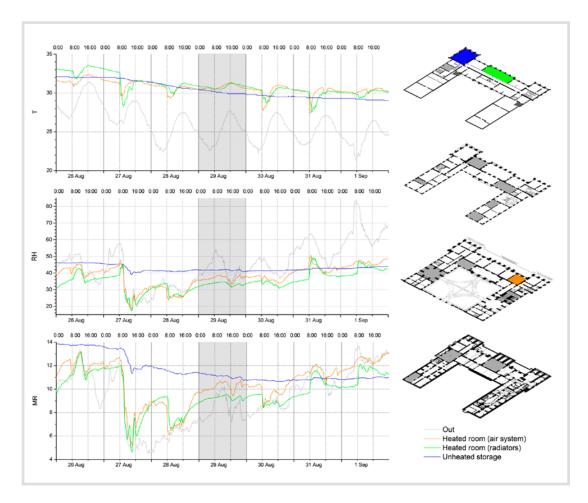
Figure 3. Weekly trends in summer in Room VII (orange), Room IV (green), and in the storage area (blue). MR = mixing ratio

As suggested in the EN 15757:2010 standard [5], the focus of environmental control should be shifted from the implementation of ideal values to understanding and evaluating existing conditions. Again, this raised a series of questions: how could the indoor climate in such a complex historic building be measured and assessed? How could the influence of old heating systems on hygrothermal factors be quantified and what were the potential consequences for the deterioration of the collection? These questions provoked reflection on the concept of historical climate and led to the development of an integrated approach to climate monitoring.

The historical climate is defined by the EN 15757:2010 standard as 'climate conditions in a microenvironment where a cultural heritage object has always been kept, or has been kept for a long period of time (at least one year) and to which it has become acclimatised'. If the historical climate can be demonstrated to be safe then it is recommended that the same environmental conditions be maintained. The case of the Villa Reale provided an opportunity to test this principle, as the historic heating system which had operated since the museum was established was still in daily use.

However, it was not possible to ascertain if the present conditions corresponded precisely to the historic environment as reliable monitoring data was not available and there had been several modifications to the museum since 1921. It was also impossible to establish a direct correlation between the present conditions and past cases of deterioration in the collection as both the content of the collection and the means of display had changed on a number of occasions over the years.

Nevertheless, studying the complex interactions between the historic air-heating system and the condition of the collections had the potential to provide useful information not only for the specific environment of the Villa Reale, but also for other collections in historic buildings that had been served by similar heating systems.

The study required an interdisciplinary approach; an indoor climate monitoring campaign was integrated with analytical tools derived from building conservation, e.g., historic and archival research, geometric surveys and endoscopic inspections [6].

Measurements have been underway since autumn 2009. Air temperature (T) and relative humidity (RH) have been monitored since November 2010. In the current article, the 13-month period from 21 June 2011 to 21 July 2012 will provide the main focus.

A procedure to establish allowable RH target ranges for hygroscopic materials in a safe historical climate is described in the EN 15757:2010 standard. Short-term fluctuations are calculated as the difference between the RH current value and the corresponding monthly central moving average. Allowable thresholds are calculated as plus or minus 1.5 times the standard deviation of this difference on a yearly basis. Nevertheless a RH range of less than plus or minus 10 % from the monthly moving average is considered excessively narrow [5]. In the Villa Reale the procedure was used for a comparative assessment of indoor climate stability in a complex building with many rooms. It was applied to both an unheated storage area, considered by

the conservator to be a good conservation environment, and to exhibition rooms where conservation problems that could be ascribed to RH variations had been noticed.

The trends in the different rooms were then compared. As the unheated storage area did not present any out-of-range fluctuations and the other rooms did (Figure 2), it was implied that out-of-range fluctuations could be considered potential indicators of increased risk. Their magnitude, frequency and distribution in different rooms was analysed and weekly trends were plotted to better understand which factors were causing potentially detrimental conditions (Figures 3 and 4).

As an alternative method, the American Society of Heating, Refrigerating and Air-Conditioning Engineers' (ASHRAE) specifications for museums [10] were used to establish a general RH target range for the whole building. ASHRAE class C, i.e., 25 to 75 % RH at all times of the year, was considered a reasonable level of climate control for a historic building like the Villa Reale.

As suggested by the Italian standard UNI 10829-1999 [7], constant permanent spot monitoring was combined with thermographic and psychrometric mapping which has been performed on site periodically to evaluate the spatial distribution of T and RH inside the rooms. This mapping had also been employed in a preliminary phase in order to select the rooms to be monitored. The selection process also took into account the orientation and position of the rooms within the building in order to optimise the information obtained from a (necessarily) limited number of measurement
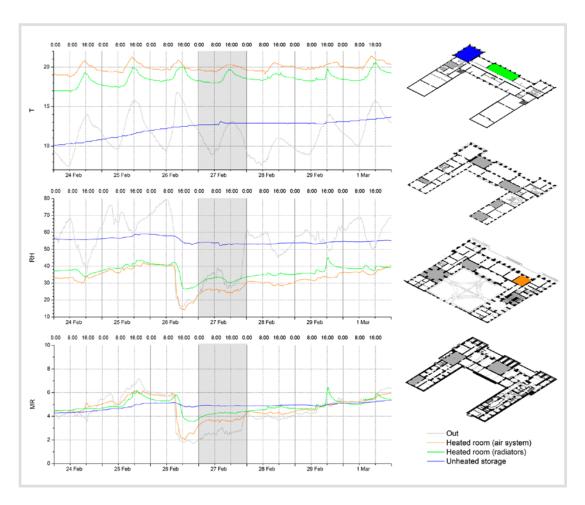

Figure 4. Weekly trends in winter in Room VII (orange), Room IV (green), and in the storage area (blue)

positions: 15 wireless WiSensys WS-DLTc sensors, transmitting to two data-loggers.

As paintings on canvas were considered to be most at risk and as convection flows were expected across the rooms, sensors were placed close to walls and at constant height (slightly over two metres from the floor), avoiding any features which might generate specific local conditions (e.g., corners and ceilings) or materials with specific thermal properties (e.g., wood, stuccos).

Thermographic imaging and psychrometric maps were used to map the surface temperature of the inner walls and to evaluate the heat and moisture exchanges between the building structure, the environment and the artworks. Thermography was also used to detect the air ducts inside the walls and to identify the presence of warm draughts on paintings.

Results and uncertainties

Villa Reale has many rooms, each with a distinct microclimate: underground storage areas, exhibition rooms (some heated by the air system, others by radiators), offices for museum staff, storage areas in the attics, as well as a number of unused rooms awaiting refurbishment.

The heating system strongly influences the indoor climate of the Villa. This is demonstrated by a comparison of the yearly trends of T and RH (Figure 2) in a heated exhibition room on the ground floor, where the old air system was still in operation (orange line), with an unheated storage area in the attic (blue line).

The heating system was in operation from mid-October to the end of April. As a consequence, during the winter the temperature in the exhibition room is much higher than in the storage area, where values are closer to outdoor conditions. RH decreases to an average level around 30 % in the coldest period, since the heating system does not incorporate any humidification. Sudden drops below 20 % RH are possible throughout the year in the exhibition rooms. The heating system has a stabilising effect on RH variations, as shown by the comparison between winter and summer fluctuations. RH and T are clearly much more stable in the unheated storage all year round.
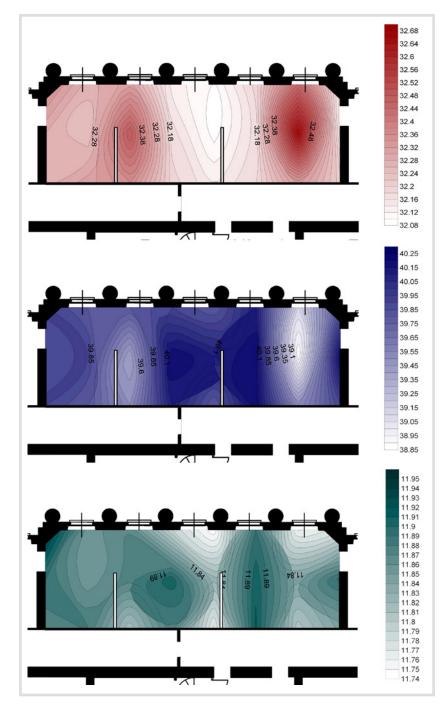
The risk of mechanical damage to hygroscopic materials is highest within conditions of both excessively low RH and where there are sudden RH variations.

Weekly trends in summer (26 August to 1 September) and winter (24 February to 1 March) presented some out-of-range fluctuations, which are shown above in figures 3 and 4. The climate dynamics were compared in three areas: an unheated storage area (blue line), an exhibition room heated by the air system (orange line) and an exhibition room heated by radiators (green line).

The data for the unheated storage area demonstrate a stable environment both in winter and in summer. Despite external walls (the room is in the attic, at the corner of the building), this storage area seems to buffer outdoor fluctuations more efficiently than the two exhibition rooms. This is mainly because windows and shutters are always kept shut in the storage area, enhancing the general

thermal performance of the building envelope and preventing the effects of direct solar radiation. It is also likely that the large amount of materials stored inside the room assists with buffering the indoor RH values. In contrast, the exhibition room shutters are either missing (as many were removed in the past) or, where they still exist, are usually kept open when the museum is open.

In the absence of a cooling system, the museum staff frequently open windows during the summer. As a result the indoor air heats up constantly during the day, particularly in the south-facing rooms (Figure 5). The consequences are evident in the daily trends (Figure 3): during opening hours (9:00 to 17:00), the indoor climate in the exhibition rooms closely follows the outdoor variations. On Mondays, when the museum is closed, and windows and shutters are more likely to be kept closed, daily variations are generally limited, even in the exhibition rooms. It is interesting to observe

how the indoor trend of mixing ratio (MR) follows a drop in the outdoor trend (27 August). In the morning, the museum attendants open the windows and let cool air in as the indoor temperature is higher than outdoors. During the day, a drop in the outdoor humidity level is immediately transmitted to the exhibition rooms while the storage area is less sensitive to this sudden change. Indoor RH and MR fluctuations overlap outdoor fluctuations until closing time, when the museum staff shut the windows. During the night, MR remains low outdoors but rises indoors, probably due to the moisture released by the walls. As a consequence, another sudden drop in indoor humidity occurs the following morning (28 August), when the windows are opened again.

During winter (Figure 4) drops in the outdoor RH and MR (26 February) produce different consequences in the two exhibition rooms. The outdoor fluctuation is buffered more effectively by the room heated with radiators than by the room heated with ventilation, into which the outdoor air is directly introduced after being warmed by the heating system.
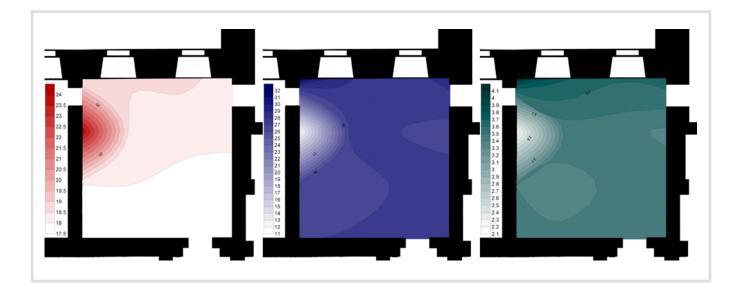
The interactions between the old air-heating system, the room microclimate and the collections were further investigated with local psychrometric and infrared thermographic mapping. One of the main concerns was that the heating system was causing differences in T and RH inside the same room. The psychrometric map in figure 6 shows that the sharpest gradients were concentrated near the air inlet, while the rest of the room maintained quite homogeneous values (ΔT = 1.5°, ΔRH = 2 %).

A remarkable air stratification was observed when the same vertical air duct connects a room on the ground floor with a room on the first floor. Thermographic images (Figure 7) demonstrate that the warm draught can pose a threat to paintings hanging near the inlet.

The heating system affects the indoor environment of the museum not only by direct air draughts. The inner walls also affect the indoor climate since the ducts circulating air to the rooms are embedded within the walls, which are not insulated. The air ducts of modern air systems are generally well insulated and do not leak heat into the building structure. In contrast, at the Villa Reale, the

Figure 6.
Psychrometric maps of T, RH and MR in Room VII (17/02/2012 – Outdoor conditions: T 8.59 °C, RH 45.7 %, MR 3.13 g/kg)

heat is transferred initially from the warm air to the walls, and then slowly released into the rooms. As a result the heating system works both through air convection and radiation. This can be localised and roughly quantified with thermography.

A similar phenomenon was likely to have been incorporated into the original thermal design of the villa through the numerous chimneys: six chimneys served the underground stoves, others the ovens in the kitchen and there were many more for the fireplaces. All these ducts increase the heat radiation of the walls in winter, while in the summer fresh air can be brought from the basement to the rooms through the ducts.

This is just one example of how the building structure (in particular the solid masonry) influences the indoor environment of this type of building. The thermal inertia of the building envelope mass also plays a key role. During the winter it slows the heat loss from the interior to the exterior, while in the summer, it slows the heat transfer from outside, helping to keep the interior fresh.

The monitoring campaign was able to detect all these peculiar phenomena but it was not possible to accurately quantify their influence.

The scatter graph in figure 8 presents data collected over a calendar year and summarises the effect of different strategies for climate control in various rooms. In the unheated storage area (blue line), RH is within the range 40 to 60 % all year long, while T has the largest range. In the heated exhibition rooms (green line, orange line), T never falls below 15 °C but RH can drop under 20 % during the winter, particularly in rooms with an air inlet.

Figure 7. Thermographic image of Room VII (8/02/2010 - Outdoor conditions: T 3.8 °C, RH 87.8 %, MR 43.7 G/KG)
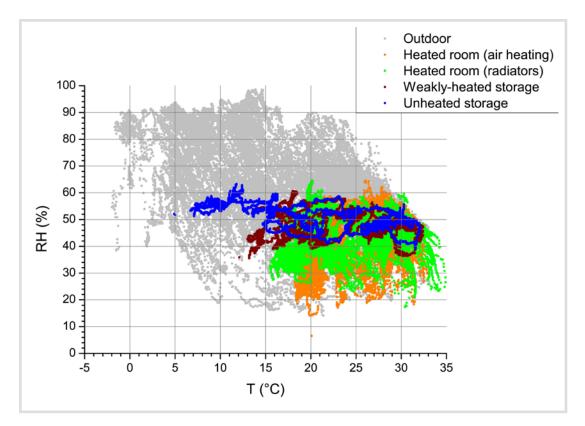
The performance of the unheated storage area in the scatter graph confirms how a passive strategy for climate control can be effective in limiting the RH range on an annual basis. Acceptable conservation conditions can be obtained by enhancing the performance of the building envelope. ASHRAE Class C conditions were fulfilled in terms of RH and it would be possible to achieve Class B conditions with relative ease.

However, an indoor temperature which drops to 5 °C in the winter is not acceptable for rooms open to the public. In addition, the high summer temperatures are uncomfortable for staff and visitors and could induce chemical deterioration in the collections (the ASHRAE chapter for museums suggests temperatures should remain below 30 °C [10]).

On the other hand, the heated exhibition rooms do not meet the Class C specifications due to their extremely low RH levels. Some form of humidification would counteract the dry conditions caused by the heating, but this is notoriously controversial in historic buildings, on account of the risk of interstitial and surface condensation. An alternative could be to reduce the temperature of the incoming air by 2 to 3 °C however this would require the heating system to be divided into different sections.

A good compromise and a possible case study for a sound climate control strategy is offered by another small storage area in the villa (represented by the dark red line in figure 8). Here windows and shutters are kept constantly shut, as in the unheated storage area, but a radiator is maintained on a constant low temperature. As a result, the temperature does not reach such extremely low values though the yearly RH range (35 to 60 %) is slightly wider than the unheated room. Short-term fluctuations and RH levels are quite satisfactory, indicating a level of control approaching AHRAE Class B for relative humidity.

Conclusions

The conclusions of this research concur with recent theory about austere Elizabethan architecture and Neo-Palladian residences: the solar orientation, position and shape of the windows, layout of the heating system and arrangement of rooms according to function were important factors in the design. It is also possible that the conservation of art was considered. We know that this was the case at Houghton Hall, designed in the 1820s, where 'it may be surmised that the cool, stable environment of the north-east corner was considered to be appropriate for the care of the paintings' [8].

Nevertheless Villa Reale was built as a private residence with no specific intention to create an indoor climate suited to artwork preservation. Subsequent refurbishments of the central heating system and modification of doors and windows have resulted in a deterioration in the indoor environmental conditions, particularly the RH control during both winter and summer.

Despite the difficulties of modelling the indoor climate of such a complex building with so little historic data, it has been possible to define the 'historical' indoor climate to some extent by monitoring the environment and linking any observed areas of concern to specific building features. An accurate description of the building, its construction and maintenance history (i.e., the heating systems, the shape of the interiors, the building structure and envelope, etc.) has been developed and will be of considerable value in establishing possible solutions.

Currently, the collected data provide confirmation of what museum conservators had already empirically suggested about environmental risks. The current environmental conditions have been created by progressive alterations in the building's function and structure; elements of the heating system have been altered and various control measures, for example the shutters, have been removed or adapted. The results also validate an aspect of current conservation practice at the museum. As paintings on display have presented more evidence of deterioration than those in storage, canvases are transferred to the safer unheated storage areas as soon as climate-induced damage is observed.

The primary objectives for future research are to further define climate-induced risk factors for the collection and to provide museum conservators with detailed instructions and preliminary mitigation strategies for controlling the internal environment.

Secondly, our aim is to understand the effect of environmental conditions on painting deterioration in more depth. By adopting a multidisciplinary approach with more detailed analysis, particular attention will be given to the question of re-lined and transferred canvases, which deteriorate more rapidly in heated conditions [9].

Finally, we aim to correct some of the current environmental problems through targeted interventions to the building structure and to the layout and regulation of the heating system.

References

[1] Blondel, J.F., De la distribution des maisons de plaisance et de la décoration des édifices en général, Paris (1737).

[2] Manfredi, C., 'The diffusion of central heating systems in Milan, Italy between the 1700s and 1800s', in The Culture of Energy, ed. M. Rüdiger, Cambridge Scholars Publishing, Newcastle (2008) 256–267.

[3] Péclet, E., Traité de la chaleur considerée dans ses applications, 3rd edn, Paris (1860–61).

[4] Middleton, R., and Watkin, D., Architettura dell'Ottocento, Electa, Milan (1980).

[5] European Standard 15757, Conservation of Cultural Property - Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials (2010).

[6] Del Curto, D., Luciani, A., Manfredi, C., and Valisi, L.P., 'Historic analysis and climate monitoring. An integrated approach to the study and management of Villa Reale in Milan', in Cultural Heritage Preservation, ed. M. Krüger, Fraunhofer IRB Verlag, Stuttgart (2011) 70–77.

[7] UNI 10829, Beni di interesse storico e artistico - Condizioni ambientali di conservazione - Misurazione ed analisi (1999).

[8] Hawkes, D., Architecture and Climate. An environmental history of British architecture, Abingdon (2012) 107–108.

[9] Fratelli, M., 'The painting begins to age on the artist's palette', in Indoor Environment and Preservation. Climate control in museums and historic buildings, ed. D. Delcurto, Nardini Editore, Firenze (2010) 5–18.

[10] ASHRAE, 'Chapter 21. Museums, galleries, archives and libraries' in 2007 ASHRAE Handbook: HVAC Applications, ASHRAE, Atlanta (2007) 21.1–21.23.

Authors

Andrea Luciani works at the Laboratorio di Analisi e Diagnostica del Costruito, a research laboratory of the Department of Architecture and Urban Studies (DAStU) in Politecnico di Milano. Email: andrea.luciani@mail.polimi.it

Carlo Manfredi is Lecturer of Architectural Restoration at Politecnico di Milano and works at the Laboratorio di Analisi e Diagnostica del Costruito. Email: carlo.manfredi@polimi.it

Davide Del Curto is Assistant Professor of Architectural Restoration at Politecnico di Milano. Email: davide.delcurto@polimi.it

Luca P. Valisi is a laboratory technician specialising in diagnostics and indoor climate analysis on historic buildings at the Laboratorio di Analisi e Diagnostica del Costruito. Email: luca.valisi@polimi.it

Uncertainties in the interaction between a canvas painting support and moisture

Anna von Reden

Abstract

The current state of research on the interaction between linen canvas and moisture is summarised by an analysis of the relevant literature. The main gaps in knowledge and key questions relating to the behaviour of a canvas painting are highlighted. Proposals are made for approaches to gain more insight into the hygroscopic behaviour of textile supports.

Introduction

Controlling the climate for art collections means dealing with objects that are sensitive to humidity and which may react hygroscopically. This applies to canvas paintings in particular. Changes in humidity, either short-term or long-term, may cause severe deformation and irreversible damage such as craquelure, cupping paint layers or even paint losses. But not only visible damage may occur. Humidity plays a crucial role in degradation processes. However, moisture treatments are the most common way of dealing with the deformation of textile supports [1]. Due to the lack of knowledge about the effects of water on a degraded canvas, it is difficult for conservators to judge a painting's sensitivity to moisture and therefore the application and dosage remains empirical.

Much research relating to the interaction between the linen canvas and moisture comes from cellulose chemistry as well as paper and textile technology. This knowledge has been adopted by conservation science, and several investigations specific to our problems and materials have been conducted in the past. Recurring debates about tolerable fluctuations in humidity demonstrate that there is still uncertainty regarding this topic. Knowledge of the precise reactions of a canvas painting in different environmental conditions is not sufficient to make predictions about the behaviour of a canvas painting exposed to differing humidities.

Intensive study of this topic during a PhD project has revealed the main gaps in our knowledge. These will be discussed with the help of a summary of the state of current research, and used as the basis for developing approaches to gain more insight into the behaviour of textile supports. The focus will be on flax as the basic component.

From molecules to the fabric structure: important components for canvas/humidity interaction
Cellulose

As the main component (64.1 %) [2] of flax, highly hygroscopic cellulose plays an important role in the interaction between a linen canvas and humidity. Inter- and intra-molecular reactions
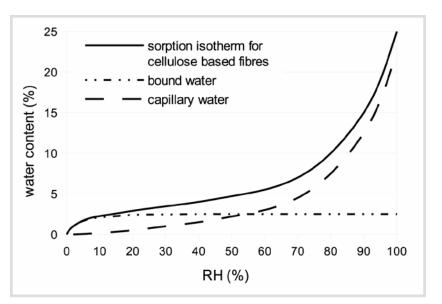
of cellulose are based on the formation of hydrogen bonds. Thus the cellulose/water interaction interferes with inter- and intra-molecular hydrogen bonds of the cellulose structure and strongly depends on the supramolecular structure of the polymer. The interaction with water is limited to the non-crystalline structural regions as well as the pore and void system. Hence the proportions of crystalline and amorphous regions of the fibres are relevant. The ratio between crystalline and amorphous cellulose varies between plant species and also depends on the processing history of the flax fibres and the cellulose degradation rate [3].

The sorption isotherm of cellulose (Figure 1) does not show a linear increase in water sorption between 0 and 100 % relative humidity (RH). The curve has a sigmoidal shape: there is a rapid increase in moisture content below 20 % RH, whereas between 20 % and 70 % RH, it increases only moderately; changes above 70 % RH are again much quicker. This is particularly important for conservation technology because even small changes in RH cause considerable changes in moisture content.

The water sorption capacity, as visible in the sorption isotherm, is linked to how water is bound in the cellulose structure: monomolecular, multi-molecular and capillary. Water that is directly bound to the cellulose surface is monomolecular. It is so strongly bound that it does not increase the volume of the cellulose in proportion to its added mass. The water making up the first 0.2 % of the cellulose moisture content is referred to as chemically sorbed or bound. This water does not act as a plasticiser and is very difficult to remove. Above 0.2 % water content, further water is less tightly bound and increases the volume of cellulose almost proportionally to the added mass (see the sorption isotherm). Between 20 % and 70 % RH, the moisture content varies between 4 % and 8 %. This so-called multi-molecular water can be present as up to 10 layers of water molecules. It is not comparable to liquid water because it is organised in a regular structure imposed by the proximity of the cellulose.

Above approximately 8 % content, water is drawn into narrow conduits or thin tubes and is held there by surface tension forces. It is referred to as capillary or pore water. This kind of adsorption may be present in small amounts at RH levels above 60 %, but

increases considerably between 90 % and 100 % RH. As the sorption isotherm shows, it is accompanied by significant swelling and weight gain. Capillary water does not have a strict structure like mono- or multi-molecular water; it can form clusters and is highly mobile [5].

Moisture sorption hysteresis is a characteristic of cellulose-based materials. This means that the former moisture content influences the current moisture content. The amount of water in cellulose at a given RH will be higher during desorption than during adsorption.

It is not only the moisture content that differs according to absorption and desorption, but also the speed of reaching equilibrium. According to Ballard, cotton fibres need 1.5 hours for sorption and 99 days for desorption to reach equilibrium at 21 °C and 65 % RH [6].

Conservators can benefit from this fact by using humidity to make canvas supports more flexible. Unfortunately, a literature search did not reveal any data for flax nor for degraded materials. Without reliable data relating to the amount and time of absorbed water for naturally-aged textiles, it is difficult to make judgements about humidification or to understand fully the behaviour of a canvas in general, for example, during fluctuations of the surrounding humidity.

The role of fibre structure

Inter- and intra-molecular hydrogen bonding between cellulose molecules creates a highly ordered arrangement for micelles, which are structural aggregates comprising about 100 cellulose chains. The structural hierarchy continues through elementary fibrils, micro-fibrils and macro-fibrils, which spiral around the axis of the fibre cell in layers. A number of such cells are bound together to form the fibre.

The plant cell of flax has a primary and a secondary cell wall. The latter is particularly thick, making up 90 % of the total cross-section of the cell. It is this cell wall that governs the properties of the fibre [7]. The angle at which the microfibrils are ordered does not seem to affect the hygroscopic behaviour. No discussion of this subject was found in the literature.

Studies of the swelling capacity of flax rarely give a clear definition of what kind of flax was used and how it was pre-treated. Nevertheless, fibre quality and their pre-processing may play a role. Koch reports the water content of flax fibres at 65 % RH to be between 9.3 % and 11.75 %, and proposes a practical value of 10 % for raw flax [8]. These variations may be due to additional components in the flax fibre, such as pectin, lignin and hemicellulose.

Elementary flax fibres are assembled into bundles held together by pectin. Pectin is composed of polysaccharides and is therefore sensitive to humidity. Enzymes destroy pectin during retting of the harvested flax plants. The method and length of the retting process determine the amount of pectin that is left in the material. During retting, pectin is reduced from 3.8 % to a residual content of 1.8 % [8]. The small proportion of pectin could be responsible for the fact that retting does not influence the sorption capacities of flax fibres [9].

Lignin is a complex amorphous polymer and is hydrophobic. With a content of about 2 % in flax [8], it is found in the middle lamella of fibre bundles.

Hemicellulose is a highly hygroscopic polysaccharide with a low degree of polymerisation. It swells to a greater extent than cellulose. With a content of about 16.7 % in flax [8], comparatively high with respect to the small amounts of pectin and lignin, it makes the highest contribution to the hygroscopic behaviour and to the flexibility of the fibre.

Even if these additional components are present in only small amounts in the fibres compared to cellulose, it is worth evaluating their role when investigating the hygroscopic behaviour of the fibrous material, which has already been carried out for pectin [9].

Owing to their longitudinal orientation, swelling of fibres exhibits significant anisotropy. Studies of viscose filaments revealed that the cross-sectional swelling is higher the finer the fibres are. It is worth evaluating whether this also applies to natural fibres such as flax. Cross-sectional swelling of flax after complete saturation with water amounts to 47 % [10]. Values for the proportion of longitudinal swelling and swelling in diameter have been reported for flax, but no absolute values for flax swelling in diameter can be found [8]. The correlation between water content and swelling in diameter may be worth studying, especially for a comparison with degraded fibres.

The influence of yarn and woven structure

The anisotropy of the fibres is transferred to the yarn because it is made of fibres. The longitudinal orientation is maintained and is responsible for the high degree of lateral swelling, although a literature search did not reveal any values for lateral yarn swelling. Whether fibre-swelling values can be transferred to the yarn can only be assumed. Furthermore, twisting fibres to make a yarn generates new pores that contribute to the water sorption properties.

Although the orientation of the yarn twist does not appear to influence the degree of dimensional changes, it may influence the direction the yarn turns during swelling and drying, which will affect the behaviour of a stretched canvas.

As each fibre swells, mainly in the lateral direction, the yarn reacts correspondingly, resulting in a shorter yarn due to the spiralling fibres. This rather small effect is superimposed by an effect caused by crimp in the fabric. When the yarns swell in width they have to cover a longer distance due to the fact that two orthogonal yarn systems wrap around each other, and therefore the whole fabric becomes shorter. Overall we can say that a raw fabric shrinks with rising humidity. This reaction of a fabric is well explained by textile technology [11]; however, contrasting results have also been observed. The situation becomes more complex when the canvas cannot expand and shrink freely, as in the case of a stretched canvas.

Mecklenburg analysed a change in the reaction of linen canvas after its first contact with high RH values. The fabric was not under tension and exhibited shrinkage as the humidity increased. After repeating the first humidification cycle, the canvas showed

a reverse reaction: rising humidity led to expansion of the canvas up to 80 % RH. The fabric began to shrink when the humidity was increased further [12].
Similar observations were made by Lipinski, who observed a reversing reaction as soon as the fabric was in contact with liquid water. The fabric was held under tension while the surrounding humidity was changed. Linen canvases reversed their reaction as soon as they had contact with liquid water. After that they expanded with rising humidity without showing a reversing point, as Mecklenburg's experiments demonstrate [13].

Various authors have discussed several factors that could be responsible for the individual reaction of a canvas: previous contact with water, as mentioned above [14], temperature [15] or density of the fabric [16], to mention only a few. In summary, there is a need for research on canvas under tension, particularly because several studies differ in their conclusions.

One main problem is that influencing parameters cannot be analysed due to insufficient information about test materials and boundary conditions. These include preparatory treatments of test materials as well as testing conditions.

Further difficulties occur when interpreting degraded material. We do not know how these canvases were prepared by the artist and we have very little information from the perspective of textile technology. The influence of this lack of knowledge has hardly been investigated due to the fact that little is known about historical methods of fabric manufacturing and how exactly artists treated their canvases before adding the ground and paint layers. Nevertheless, these factors must play a role in the behaviour of the canvas as the example of bleached textiles demonstrates.

The author's own studies show that historical bleaching processes lead to reduced water sorption in linen fabrics. Fakin et al. [17] analysed the influence of an alkaline pre-treatment before an oxidative bleaching process on the water-sensitivity of flax fibres. This treatment is fundamentally comparable to a historical bleaching process [18]. The alkaline pre-treatment leads to a slightly higher moisture sorption of the fibres that was reversed by the subsequent bleaching process. After bleaching, flax fibres exhibited their initial sorption capacities. Whether these findings on modern bleaching processes are transferrable to historical bleaching techniques requires further investigation.

Reactions of a painting

The behaviour of a painting differs from a raw fabric in that one side of the tensioned canvas is coated with various layers of glue, grounding and paint with differing compositions. The difficulty in describing its reactions lies in its individual composition and degradation history. The complexity lies in the interaction of the canvas with the additional layers that form the painting.

Most of the conservation-related findings concerning the behaviour of canvas paintings are based on observations of changes in dimension or tension when exposed to different humidities. Special attention was paid to the size layer, which is the first preparatory layer of a canvas used as a painting support. Both materials are highly hygroscopic but exhibit different types of behaviour. Several

authors have confirmed that the behaviour of a raw canvas exposed to high humidity is reversed after application of a size layer. This is true up to 70 to 80 % RH: the glue layer then loses its coherence, which is why the reaction of the canvas is again dominant. There is no exact value, only a range, of the humidity at which this turning point will occur [13].

Many investigations comment on the behaviour of the canvas and the size layer though much less is published concerning the ground and paint layers. The main problem is the reverse reaction of the hygroscopic fabric and the glue-based materials versus materials that are less sensitive to humidity (e.g., oil-based paint layers).

Mecklenburg presented a computerised model of the behaviour of a painting based on the analysis of each single layer of the whole painting [19]. Although this is a useful approach, considerably more information about the single layers must be collected before the basic data can be interpreted.

Changes in behaviour during ageing

All of the information summarised above is mainly related to new material. Degraded materials behave differently. Assumptions about the behaviour of degraded linen canvases are essentially based on our understanding of cellulose degradation. The extent to which these findings can be transferred to the behaviour of degraded canvases has not been completely clarified. The degradation process is affected by different structural hierarchies: cellular, fibrous, yarn and fabric structure.

The few existing studies of the behaviour of degraded materials at different humidities do not provide information on the degree of degradation. Consequently, relationships between the condition of the molecular cellulose and the hygroscopic behaviour of the canvases cannot be established. Due to the fact that investigations on naturally degraded material are only possible to a limited extent, our knowledge is mainly based on studies of artificially aged materials. For example, a search revealed only one sorption isotherm for a naturally aged linen canvas dating from the sixteenth century [20].

Two changes that are assumed during ageing of linen canvases will be discussed in greater detail: the increasing degree of crystallinity and the decreasing degree of polymerisation.

Previous contact with humidity and water influences the behaviour of textiles. It is assumed that repeated humidification leads to a reduced water sensitivity. On the one hand, a higher moisture content increases the degradation rate due to enhanced hydrolysis. This does not proceed in a linear relationship with respect to the surrounding RH. The degradation rate increases with rising moisture content and thus corresponds to the slope of the sorption isotherm of cellulose [21]. On the other hand, humidity cycles may lead to pronounced changes in cellulose structure, which is not completely reversible after drying. This may result in increasing crystallinity and therefore less water sensitivity. Humidity cycles are considered to have an even higher degradation effect on cellulose-based materials than a constant high moisture content [22, 23].

On the basis of studies of synthetic fibres, Timár-Balázsy points out that materials with a lower degree of polymerisation have a higher moisture regain. It seems probable that this is transferable to native fibres, however, this has not yet been verified.

It remains uncertain how far existing theories of degraded material at the molecular level can be transferred to linen canvases. Direct correlations between these single aspects and the response to humidity have not been fully analysed. Can we correlate the larger amount of crystalline regions with a lower capability of binding water? And how does this correlate with the higher moisture regain at lower degrees of polymerisation?

Lack of knowledge and the challenge for future work

It is apparent that there is an imbalance in our understanding of the relationships between cellulose at the molecular level, the structure of fibrous materials and the behaviours of yarn, fabric and paint. As the hierarchy of the composition of a painting becomes more complex, our understanding of its behaviour becomes less detailed.

The relatively good basic knowledge at the molecular level of cellulose is based on contributions from a variety of disciplines. These findings must always be carefully examined as to whether they can be transferred to the field of conservation science. This was realised quite early on and correspondingly applied to research in the field of conservation. The main difficulty in interpreting work published in the field of conservation science is the often insufficiently defined material used in the investigations. Cause and effect cannot always be determined exactly. It is essential to evaluate the impact of fibre composition as well as the historical processing method by the artist and also to consider the problem from the perspective of textile technology.

One of the main deficits is the correlation of molecular considerations with the behaviour of naturally aged painting supports. Which parameters are relevant for investigating the hygric behaviour of an aged textile support? At the molecular level, one can consider the crystallinity index, degree of polymerisation and amount of constituents alongside cellulose, without knowing which influences are dominant. All the findings at the molecular level concerning ageing of cellulose have not been sufficiently substantiated with naturally aged materials.

The aim has to be to find causal links between the condition of a degraded textile and its capacity to bind water, the resulting hygroscopic behaviour as well as its physical characteristics. The wide range of different reactions of degraded canvas supports may be a result of either the original material itself with its individual processing or in the individual ageing it has experienced. Most likely, it is a combination of both. To obtain a more differentiated insight into this behaviour, further in-depth studies focussing on single aspects are required, which must maintain their connection to naturally aged paintings. This article highlights a few aspects that will be studied in the PhD research mentioned above.

An essential element for understanding the hygroscopic behaviour of painting supports is a good basic knowledge about their water-

binding capacity. There is very little data currently available on the reduced water-binding capacity of degraded material. Investigations during the PhD research will concentrate on the sorption behaviour of degraded materials, especially the amount and speed of adsorption and desorption. Sorption isotherms will be registered on artificially and naturally aged linen canvases to investigate whether the sorption capacity changes to the same extent for all ranges of RH. To estimate the rate of degradation, parameters such as the degree of polymerisation, crystallinity index, pH and mechanical testing will be recorded, and the corresponding data will be analysed for correlations between these parameters and the sorption properties.

In addition to sorption isotherms, near-infrared spectroscopy, another method of detecting the water content in the textile and canvas painting, will be evaluated to consider if this analytical technique can be used for in-situ analysis of the moisture content.

Further work required includes studying the amount of swelling and its effect on the fabric. Does a reduced sorption capacity lead to the same reduced swelling capacity of the fibres and therefore a lesser tendency toward fabric shrinkage? One possible approach is to investigate fibres by means of environmental scanning electron microscopy [24].

To achieve more insight into some of these aspects, it will always be useful and necessary to study artificially aged materials. Substantiation of the results using original painting supports inevitably requires development of techniques to investigate historical materials in minute quantities, as demonstrated by Chan et al. [25].

Acknowledgements

References

[1] Ackroyd, P., Phenix, A., Villers, C., and Wade, N., 'Structural treatments for canvas paintings in 2002: summary of questionnaire replies', in ICOM Committee for Conservation, 13th triennial meeting preprints, Rio de Janeiro 2002, ed. R. Vontobel, James & James, London (2002) 321–327.

[2] Tímár-Balázsy, Á., and Eastop, D., Chemical Principles of Textile Conservation, Butterworth-Heinemann, Oxford (1998).

[3] Klemm, D., Philipp, B., Heinze, T., Heinze, U., and Wagenknecht, W., Comprehensive Cellulose Chemistry – 1: Fundamentals and Analytical Methods, WILEY-VCH, Weinheim (1998).

[4] Morton, W.E., and Hearle, J.W.S., Physical Properties of Textile Fibres. 3rd Edition, the Textile Institute, Bath (1993).

[5] Banik, G., and Brückle, I., Paper and Water: a guide for conservators. Butterworth-Heinemann, Oxford (2011).

[6] Ballard, M.W., 'Hanging out. Strength, elongation and relative humidity: some physical properties of textile fibres', in ICOM Committee for Conservation, 11th triennial meeting Preprints, Edinburgh, 1996, ed. J. Bridgland, James & James, London (1996) 665–669.

[7] Cuissinat, C., and Navard, P., 'Swelling and dissolution of cellulose. Part III: Plant fibres in aqueous systems', Cellulose 15 (2008) 67–74.

[8] Koch, P.-A., 'Faserstoffe', in Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, ed. E. Schmidt, Springer, Berlin (1955) Band IV Teil 1.

[9] Schroth, T., Untersuchungen zur Weiterentwicklung der Flachsröste, Universität Hohenheim, Stuttgart (1995).

[10] Morehead, F.F., 'Some comparative data on the cross-sectional swelling of textile fibers', Textile Research Journal 17 (1947) 96–98.

[11] Abbott, N.J., Khoury, F., and Barish, L., 'The mechanism of fabric shrinkage: The role of fibre swelling', Journal of the Textile Institute 55 (1964) T111–T127.

[12] Mecklenburg, M.F., 'The structure of canvas supported paintings', in Preprints to the Interim Meeting: International Conference on Painting Conservation. Canvases: Behaviour, Deterioration and Treatment. 9-11 March 2005, ed. M.C. Agustí, L.F. López, S.M. Rey, V.G. Blay, Universidad Politécnica de Valencia (2005) 119–155.

[13] Lipinski, W.-H., Untersuchungen zum feuchtephysikalischen Verhalten von Gemälden auf textilem Bildträger unter biaxialer Dehnung, Staatliche Akademie der Bildenden Künste Stuttgart, Stuttgart (2010).

[14] Mager, S., Leinwand ohne Spannrahmen in der zeitgenössischen Kunst: Bildträger mit besonderen Eigenschaften und Anforderungen, Diploma thesis, Cologne University of Applied Sciences, Cologne Institute of Conservation Sciences, Cologne (2007) (unpublished).

[15] Russell, W.H., and Berger, G., 'The behaviour of canvas as a structural support for painting', in Science and Technology in the Service of Conservation, Preprints of the IIC Washington Congress 1982, International Institute for Conservation, London (1982) 139–145.

[16] Berger, G.A., and Russell, W.H., 'Investigations into the reactions of plastic materials to environmental changes, Part I: The mechanics of the decay of paint films', Studies in Conservation 31 (1986) 49–64.

[17] Fakin, D., Golob, V., Stana Kleinschek, K., and Majcen Le Marechal, A., 'Sorption properties of flax fibers depending on pretreatment processes and their environmental impact', Textile Research Journal 76.6 (2006) 448–454.

[18] Heydenreich, G., Carson, D., Grzywacz, C., Khanjian, H., Mazurek, J., and Schilling, M., 'Painting on white canvas: sixteenth-century bleaching practices and analysis of morphological and chemical changes in flax fibres', in ICOM Committee for Conservation, 15th Triennial Meeting preprints, New Delhi, 22–26 September 2008, ed. J. Bridgland, Allied Publishers, New Delhi (2008) 609–618.

[19] Mecklenburg, M.F., and Tumosa, C.S., 'Mechanical behaviour of paintings subjected to changes in temperature and relative humidity', in Art in Transit: Studies in the Transport of Paintings, International Conference on the Packing and Transportation of Paintings, London 1991, National Gallery of Art, Washington (1991) 173–216.

[20] Wyeth, P., 'Signatures of ageing: correlations with behaviour', in Scientific Analysis of Ancient and Historic Textiles: informing preservation, display and interpretation: postprints, ed. R. Janaway, P. Wyeth, Archetype Publications, London (2005) 137–142.

[21] Zou, X., Uesaka T., and Gurnagul, N., 'Prediction of paper permanence by accelerated aging I. Kinetic analysis of the aging process', Cellulose 3 (1996) 243–267.

[22] Shahani, C.J., Hengemihle, F.H., and Weberg, N., 'The effect of variations in relative humidity on the accelerated aging of paper', in Historic Textile and Paper Materials II: conservation and characterization, ed. S.H. Zeronian, H.L. Needles, American Chemical Society, Washington D.C. (1989) 63–80.

[23] Käßberger, M., Vorgänge im Papier bei dynamisch beschleunigter Alterung, Technische Universität Graz, Graz (1998).

[24] Haller, U., 'Gemälde im VP-REM: Beobachtungen zum Feuchteverhalten von Werkstoffen der Malerei. Eine Projektskizze', in Wasser, Beiträge zur 20. Tagung des Österreichischen Restauratorenverbandes Nov. 2006, ed. Österreichischer Restauratorenverband, Remaprint, Wien (2007), 20–27.

[25] Chan, T.Y.A., Odlyha, M., and Scharff, M., 'In situ dielectric analysis for canvas paintings', The Conservator 19 (1995) 10–19.

Author

Anna von Reden is a paintings conservator currently working on a PhD project about the hygroscopic behaviour of linen canvases as painting supports at the Dresden Academy of Fine Arts. Email: annavreden@gmx.de

Licence

Monitoring complex objects in real display environments – how helpful is it?

Naomi Luxford and David Thickett

Abstract

The application of accelerated ageing experimental results to real life environments and collections can be problematic. Similarly, monitoring small changes and understanding objects on display is complex and can be difficult. Veneer and marquetry furniture collections are often reported to be vulnerable, particularly to relative humidity (RH) fluctuations. As a result stable environments are recommended for display conditions, however without air conditioning, as in historic houses, these can be difficult to achieve. This paper outlines the problems and issues around monitoring complex objects in real display environments. Details of the selection of the objects, their materials and unknown histories as well as the monitoring techniques, their use and application in non-laboratory environments are included. The data provided by monitoring techniques and how they can be interpreted will also be discussed. Crucially, the paper will examine whether the outcomes of such monitoring are useful and helpful to both scientists and conservators, particularly in relation to the alternative accelerated ageing methods.

Introduction

One reason for accelerated ageing simple surrogate materials is the complex nature of real objects. Most historic objects will have different previous historical environments, which affect the current condition of individual items in the collection in different ways. Scientists can make assumptions about the historical conditions prior to environmental monitoring or under different heating regimes or occupation levels, but the entire previous history of an object is rarely known. Similarly, production methods and materials are likely to be largely unknown and probably varied, particularly if regular restoration or conservation has occurred. Such factors mean the number of potential variables is large and the problems being studied are complex. Accelerated ageing has often been preferred to monitoring changes in real objects as to attempt the latter requires the measurement and extrapolation of very small changes [1].

In accelerated ageing experiments the complexity of real objects is reduced to a smaller number of common elements. Surrogate materials are subjected to known environments or test conditions to study changes and deterioration. New materials are often used to replicate historic objects found in collections. Destructive forms of analysis can be undertaken on surrogate materials, which would often be impossible to consider on objects within historic collections. These studies are frequently conducted on the individual components which make up a complex, layered structure or object [2, 3]. The simple surrogate materials are subjected to accelerated ageing using artificially increased exposures to light, heat, relative humidity, pollutants or combinations of these factors

and others, to assess whether and in what ways deterioration takes place. From accelerated ageing experiments and observations, recommendations for display and storage environments or preferred interventive treatments are then made.

There are numerous criticisms of accelerated ageing as a technique. Doubts have been expressed about whether accelerated ageing produces the same reactions at the same comparable rates as 'real-life' deterioration factors at work in display environments; different, possibly even new, deterioration mechanisms may dominate. There are also questions surrounding whether the results can be extrapolated back to display conditions successfully, and about how representative new materials can be of historic objects [1]. The methods and results have thus been challenged in numerous respects. However, our understanding of how historical materials behave is limited and these methods can provide a baseline of information. An alternative is to monitor real objects in real collections in all their complexity. This means finding ways of studying very small changes and having sufficiently long timescales for experimental aspects. The work presented here has moved beyond environmental monitoring and accelerated ageing experiments on surrogates, to look at real collections in real environments. The research focuses on veneer and marquetry furniture, commonly regarded as vulnerable objects, particularly to changes in RH [4].

Veneer and marquetry objects are formed of a number of hygroscopic layers, each with varying response rates. The solid wooden carcass is assumed to respond slowly to changes in RH due to its mass, while the thin wooden surface layers respond rapidly depending on the coatings that form the outermost layer; furthermore, the thin (usually animal protein) glue layers are affected at different RH levels to the wood. These materials can, and have been studied as individual layers [2, 3]; however, there has been little research on their behaviour in composite objects. Despite this, their assumed vulnerability [4] leads to display recommendations that require tightly controlled environments, realistically only achievable with air-conditioning. Typically recommended museum environments for such objects are 50 % RH, plus or minus 5 %, or even smaller fluctuations [5]. However, historic houses in the UK rarely have air conditioning and their display environments can vary dramatically from those in conventional museums. This research focuses on the actual effects of these environments on collections as they are displayed. The aim is to understand more clearly the extent of the risk these conditions pose, and whether environmental control could be improved.

Object selection

An initial review of English Heritage's Heritage Object Management System (HOMS) identified which properties had large numbers of veneer and marquetry furniture. The properties were visited to inspect both the collections and the environment and to assess options for monitoring. After visiting Kenwood House (Figure1), an English Heritage property in north London, options were discussed at meetings with curators and site staff. Kenwood House was selected as the case study site and collections monitoring has taken place over a 12-month period. The monitoring has involved the conventional display environment measurements but

also analysis of the objects themselves. A period of 12 months was selected to account for the daily, monthly and seasonal cycles that take place naturally in such hygroscopic materials. Although better known for its outstanding collection of old master paintings, Kenwood House also has a notable collection of veneer and marquetry furniture, mainly dating from the eighteenth century. Kenwood House has also previously posed environmental problems, with very low winter temperatures being necessary in the display rooms to maintain the RH levels due to conservation heating. A further reason for selecting Kenwood House as the case study site was its proximity to UCL, which simplified the processes of transporting monitoring equipment.

For the majority of the monitoring techniques six objects on display and three in storage were analysed (Table 1). All the selected objects were part of the Kenwood House collection and were located in display rooms or stores. Their condition varied, with those in storage generally in poorer states than those on display. Each object had a range of wood veneer and marquetry patterns or details and, in some cases, colours. Although this provided a wide range of variables it was hoped that by examining a large number of alternatives the results would be applicable to collections beyond Kenwood House. Some additional objects were monitored to provide additional data, for example, two acoustic emission (AE) sensors were available; however the selection of objects was limited by available power supplies. The floral commode and piano were analysed primarily because there were available power supplies nearby.

Monitoring techniques

The selection of monitoring techniques was based on two main criteria: access to equipment and portability and ease of use on site. Kenwood House already had a telemetric environmental monitoring system, recording temperature and RH. The equipment

Figure 1. Kenwood House, English Heritage

used to monitor the furniture collections was selected from both English Heritage and UCL's Centre for Sustainable Heritage. Initially it had been planned to undertake laboratory testing of the various techniques to determine those most suitable for on-site use. However, this proved impractical due to building work at Kenwood House so equipment was tested in the stores to determine how practical it was to use on site. This was followed by monitoring in the display rooms alongside further monitoring in the stores until they closed as part of the building project. The monitoring equipment used on site included: AE sensors (Figure 2), colorimetry (Figure 3), near-infrared (NIR) spectroscopy (Figure 4), three-dimensional (3D) surface profilometry (Figure 5) and imaging the objects, including compiling polynomial texture maps (PTMs) (Figure 6) [6]. In addition to these techniques a trial using Digital Image Correlation (DIC) and commercial software

Table 1. Analysis techniques used for objects from Kenwood House

Image	Object description	Location	Monitoring techniques
	Left-hand marquetry table	Dining Room	Colorimetry, near-infrared spectroscopy (NIR), Surface profilometry
	RHS marquetry table	Dining Room	Colorimetry, NIR, Surface profilometry
	Carlton writing desk	Breakfast Room	Colorimetry, NIR, Surface profilometry
	Lemon table	Lady Mansfield's Dressing Room	Colorimetry, NIR, Surface profilometry, polynomial texture mapping (PTM)
	Pier table	Housekeeper's Room	Colorimetry, NIR, Surface profilometry, PTM
	Floral commode	Housekeeper's Room	AE, Colorimetry, NIR, Surface profilometry
	Piano	Music Room	AE
	Table	Furniture Store	Colorimetry, NIR, Surface profilometry
	Commode	Furniture Store	Colorimetry, NIR, Surface profilometry
	Writing desk	Furniture Store	Colorimetry, NIR, Surface profilometry

Figure 2. Acoustic emission sensor on the floral commode at Kenwood House

Figure 3. Colorimeter on the LHS marquetry table top at Kenwood House

Figure 4. Near-infrared spectrum being recorded on the Carlton desk at Kenwood House

Figure 5. 3D surface profilometry equipment

Figure 6. Taking photographs to compile PTMs

Figure 7. Imaging set up in lab for DIC

(StrainMaster) was undertaken in the lab (Figure 7) [7]. This will be discussed in relation to how it might be used on site.

As part of the research a number of public dissemination events were organised. These had two aims, to share the research and information about heritage science with the public and also to ensure equipment was not moved or tampered with during the on-site monitoring. One very simple way of sharing information was to include additional time to answer questions while on site for the analysis, which was undertaken during house opening hours. Additionally, details on each monitoring technique were added to the interpretation sheets within the rooms containing veneer and marquetry furniture, to provide information when the researcher was not present. A small exhibition (Figure 8) was also created for Kenwood House to disseminate the research and gather data on public perceptions of damage for veneer and marquetry collections. Finally, tours were offered to visitors to give more-in depth-explanation of the research. This work has been presented elsewhere [8] however it was successful in preventing equipment tampering and sharing the research with the public, with over 1500 responses to the interactive damage survey in the exhibition.

As a result of using the various monitoring techniques on site a series of criteria were drawn up against which the practicalities of the techniques used were assessed. Table 2 outlines the criteria, scores and comments for each technique. The table has been completed by the researcher and is a personal response based on experience of using the techniques. Although the opinions are based on specific instruments for each technique, there are also some general points on use so it is hoped the table can provide information on techniques which may be new to a conservation audience. Scores were awarded from 0 to 10, with 10 being the most positive value, so highest is better when interpreting the total scores. In each case brief comments are also provided to give an explanation and more detail.

Considerations for physical use of equipment included how heavy or big it was for transporting to and from the site, but also for taking measurements on site. For example the portable

Figure 8. Exhibition at Kenwood House explaining Change or Damage? Research project

NIR spectrometer weighs approximately 2 kg, which although not very heavy can lead to tired arms when each measurement takes around a minute. Other practicalities included how easy the software was to use and how much data manipulation was possible, how long it took to collect the data on site, whether it was a spot or continuous monitoring technique and the repeatability of the measurements. A general comment on how usable the techniques are and whether the whole object or small areas were analysed. One further consideration was whether the technique was non-destructive (i.e., does not cause damage to the object or sample), non-invasive (i.e., does not require a sample) or non-contact (i.e., does not need to be placed on the object or sample). Many imaging techniques are now non-destructive, non-invasive and non-contact, allowing the monitoring and analysis of materials without any changes to the object. Techniques which are non-destructive, non-invasive and non-contact are seen as the optimal future methods for heritage science.

Data and interpretation

An important consideration when assessing the monitoring techniques was the data outputs and how easily these could be determined and interpreted. This includes whether further processing or additional software was required. Criteria included in table 2 under this heading include the quality of information produced, how easy the data is to interpret, the amount of data processing required and how easy it is to compare the results with those from other techniques. The latter point can be a key consideration when calculating ease-of-use, for example, although NIR spectra are usually very quick to collect, the individual spectra require comparison with a robust database if the technique is being used for identification, or substantial processing to determine small changes in the materials analysed or to create predictive models [9]. This processing of creating databases is not straightforward and requires substantial background knowledge and experience. The amount of data processing or interpretation can ultimately impact on the usefulness of a technique and its application in the heritage field. Techniques which require expensive additional software or time-consuming processing and interpretation to answer relatively routine questions are unlikely to be seen as effective.

Acoustic emission

Although the AE sensors recorded a signal, when it was compared with environmental data there was a correlation with room temperature, which led to variation in the signal below 10. The equipment manual for the AE sensors gives a default filter value of 10 but no indication why this value was selected, however the most likely reason is the temperature variation. Apart from the temperature variation no AE signals were recorded. There are a number of possible reasons for this, the environment may have led to no changes in the objects, or the sensors may have been placed in areas where no signal was being emitted; alternatively, the sensor head may not have been in sufficient contact with the surface. In industrial applications, the sensor head is held in place using glue or grease, which is obviously inappropriate for historic collections so the manufacturers include a weight to maintain contact with the surface. Previous studies have placed archival polyester sheets (Melinex) between the sensor and object surface to provide improved coupling [10].

Table 2. Analytical techniques assessment

technique	acoustic emission (AE)		colorimetry		digital image correlation (DIC)		near-infrared spectroscopy (NIR		polynomial texture mapping (PTM)		surface profilometry	
equipment	woodwatch (Hanwell)		CM-2600d (Minolta)		StrainMaster (LaVision)		PhazIR (Polychromix)				TRACEiT (Innowep GmbH)	
criteria	score	comment	score	comment	score	comment	score	comment	score	comment	score	comment
practicality of use – physically	6	easy to place on object but requires power	10	small and light, changeable measurement size	5	bulky tripod & laptop	6	portable but heavy when holding for long periods	7	once set up the image capture is straight-forward	6	requires laptop and drains battery, difficult to hold still on vertical surfaces
practicality of use – software / interface	3	limited control over parameters and impact of changes unclear	4	usually export data into another package to calculate colour change (ΔE)	2	requires training / specialist	5	limited capabilities unless identification programme already established	7	once familiar it is very easy but limited information on how to use	5	limited control over parameters, hard to manipulate data
quality of information produced	3	graphs of recorded emission	8	gives Lab and spectral reflectance	2	requires training / specialist	7	good quality spectra but over very limited range	3	images are good dissemination tool rather than analytical	6	3D maps and slices nice but limited ability to compare measurements
ease of data interpretation	2	difficult to understand output in relation to cause	4	requires further processing to understand values	8	detailed info on deformation / strain	2	spectra difficult to compare / analyse without additional processing eg., MVA	1	images are good dissemination tool rather than analytical	4	difficult to determine changes from 3D maps alone
amount of data processing required	5	similar to other products but need to know start date and time	4	need to calculate ΔE / process spectra - can be time-consuming	10	none carried out by specialist	2	very significant as can only be exported as table which cannot be imported to baseline correct	8	little processing required beyond creating folders and ensuring images have right file ending	5	can be time-consuming if analysing outside of provided software
time to collect data	3	probably need 12 months of data to determine impact	9	very rapid once positioned	5	image collection fast but set-up time-consuming	6	around 60 seconds per spectrum depending on number of scans	2	taking large number of good quality images is time-consuming	4	takes around 5 minutes per measurement (incl. calculating maps)
non-destructive vs. non-invasive vs. non-contact	6	non-destructive, non-invasive depending on sensor attachment method	8	non-destructive, non-invasive	10	non-destructive, non-invasive, and non-contact	8	non-destructive, non-invasive	9	non-destructive, non-invasive, could be non-contact depending on use of snooker ball / lighting rig	7	non-destructive, non-invasive, could be destructive if lifting sections placed under measuring head edge
spot / continuous monitoring	5	continuous but requires constant power	6	spot but requires very good repositioning	10	can be either but large datasets if continuous	3	spot but very difficult to reposition due to large measuring head	4	spot but difficult to compare measurements with one another	5	spot but requires good repositioning and 12 months data
repeatability of measurements	0	systems were not compared against each other	3	if repositioning not exact large colour changes will be recorded	8	dependent on experimental set up being repeatable	3	if repositioning not exact, differences will be recorded	2	difficult to compare any repeated measurements	3	if repositioning not exact differences will be recorded

technique	acoustic emission (AE)		colorimetry		digital image correlation (DIC)		near-infrared spectroscopy (NIR		polynomial texture mapping (PTM)		surface profilometry	
equipment	woodwatch (Hanwell)		CM-2600d (Minolta)		StrainMaster (LaVision)		PhazIR (Polychromix)				TRACEiT (Innowep GmbH)	
criteria	score	comment	score	comment	score	comment	score	comment	score	comment	score	comment
magnitude of measureable change vs. replacement error	0	n/a	3	replacement error high compared with colour change results	7	relies on image matching but very sensitive method	3	errors high as replacement is difficult due to measuring head	0	n/a	3	quoted decimal places for measurements are greater than the instrument accuracy
ease of data comparison – with other techniques	0	no emissions recorded so cannot compare with other techniques	7	results can be exported as comma separated value (csv) but requires data processing, so time-consuming	4	data sent as images so only a subjective comparison is possible, would require more data from manufacturers	3	results exported as csv but requires substantial data processing and additional software to be really possible	2	may provide additional support images for other techniques but qualitative data makes this of limited use	4	software is restrictive so comparison is possible but requires additional analysis, more information might be available using alternative software
ease of data comparison – with environmental data	8	easy to compare with T/RH data but time interval may require some processing	4	for new lab samples colour changes can be seen after light exposure	4	if running continuously comparison might be easier but the before and after images result in an averaged effect	2	in the work so far this has not been possible but further data analysis may identify effects which relate to environmental data	2	may provide additional support images to show impact of environment but qualitative data makes this of limited use	3	data processing is required to see whether the changes observed on screen actually relate to environmental changes
quantitative vs. qualitative data	6	no emissions recorded but should be quantitative	7	quantitative data as long as correctly repositioned	8	quantitative data possible using high resolution images	7	quantitative data as long as correctly repositioned	3	qualitative images	5	quantitative but requires significant additional processing as initial results are really only qualitative
scale of analysis eg., number of small areas vs. whole object	5	depends on sensor number, 1 sensor gives local analysis but 3 can pin-point area of damage	5	small area but fast so can do greater number although this increases data processing	7	whole object in detail but depends on camera resolution / object size	5	small area but quick so can do greater number although this increases data processing	4	depends on camera field of view but relatively small areas	3	small area and time-consuming process limits the number of areas possible for analysis
usability	3	software too restrictive and help manual very poor making it very hard to use as off-the-shelf product	7	limited instruction required on use but analysis more complex	2	requires manufacturer specialist	5	data collection easy, data processing difficult	6	relatively low-tech set up, software is free, but limited resulting information	5	data collection easy, data interpretation difficult
total (higher better)	55		89		92		67		60		68	

Colorimetry

The colorimeter has a viewing window to enable it to be lined up and measurements be repeated. However, comparison of the data collected on site showed a large variability in the size of changes recorded between each month. Tests to reposition the colorimeter demonstrated that the repeatability ranged from $\Delta E00 = 0.2$ up to 2, therefore only colour changes greater than $\Delta E00 = 2$ can be seen as actual colour changes. When comparing this with the data recorded on site no real trends could be observed. In the analysis of new lab samples, changes after light exposure followed an obvious trend, with additional changes after further light exposure. On site these patterns could not be observed. This may arise as a result of the furniture having already been faded or darkened to the maximum extent possible for the material in question. To calculate the colour changes for all the samples took a substantial amount of time due to the large number of data points (for the display objects 150 spectra were recorded every month and 13 months' of data were analysed). Additionally, some multivariate analysis (MVA) was undertaken on the spectra, which has been useful in separating the different coloured woods, for example, the white and cream sections from lighter brown woods. MVA uses matrix algebra to highlight correlations within large data sets, for example the entire reflectance spectra for colorimetry or NIR, helping to identify small differences in data.

Digital image correlation

Digital image correlation was only available in the lab and was on trial from the manufacturers. However, as the technique showed potential for heritage applications it has been included in the analysis. Although DIC can be used to look at whole objects the trial showed better results when looking at smaller areas, focusing on details of the marquetry pattern. DIC can analyse 'before' and 'after' images or alternatively can be used to continuously monitor the area/object, although this generates very large datasets. Industrially, it aligns an array of dots applied to the surface to determine the movements and strains which have occurred in the object. This dot matrix is not suitable for heritage objects; however, the technique has already shown some application for tapestries [11] and wall paintings, using the surface image to align the images. The trial demonstrated that small dimensional changes and strains, resulting from RH chamber experiments, could be mapped on the surface. A potential problem when using this technique on site would be surface reflections from varnished or highly polished surfaces, as the technique struggled with these types of samples in the lab. Another possible issue on site would be positioning the equipment as the set-up can be quite bulky and has to be undisturbed, which would probably require a portion of the room in front of the object to be roped off during analysis. However, the technique is very sensitive to surface movements and strain development, and has potential for application as both a monitoring tool and a means of recording damage.

Near-infrared spectroscopy

As mentioned above, the main problem with NIR spectroscopy is the requirement for large amounts of time-consuming data processing to interpret the spectra. Preliminary MVA interpretation of the spectra has shown clear differences on objects where one

side is visibly faded compared to the other, e.g., the commode in storage. However, further work is required to determine whether real changes can be observed to be taking place over the monitoring period. One disadvantage of this NIR spectrometer is the large measuring head and the lack of precision when repositioning it, as the exact location of the light cannot be observed. In practice, to try to overcome this limitation the rectangular measuring head was lined up with areas or decorative features on the objects, however large variability is to be expected. For the aged lab samples, different surface coatings could be clearly separated using the NIR spectra. However, if there were differences in the display object coatings, these were not apparent from the spectral analysis.

Polynomial texture mapping

Polynomial texture mapping images were made of two object surfaces. Capturing the photos to create the PTMs required substantial space in the display rooms compared with the other monitoring techniques and so was only carried out when the house was closed to the public. The objects selected for these techniques had noticeable surface lifting, which the imaging was used to capture. For objects with flat or very reflective surfaces the PTM would either show little difference or the light reflections would be difficult for the software to eliminate. The results from this technique are interesting and useful in demonstrating how surfaces can be visualised. However, they provide qualitative information and are mainly useful as a dissemination tool, for example, to demonstrate that sections of veneer are lifting. This may be useful for documentation of objects, but the software does not currently facilitate comparisons of images and so there would be no way of directly determining the movement between two PTMs.

Surface profilometry

This technique uses light to create three-dimensional maps of small areas on the surface. Though the measuring head is small, it is powered by the connected laptop, which reduced the laptop battery life to two hours. An additional battery would be essential to complete site work where access to power was limited. Although movements can be seen between images taken over different months, caution is required as they are not necessarily perfectly aligned. When taking measurements, the live feed allows the camera to be repositioned, however, each 5 x 5 mm square is compiled of a square of 1500 x 1500 data points which means the exact data point is unlikely to align precisely on different occasions. A further complication is that the software automatically gives the first x, y point a 0, 0 value. So datasets cannot easily be subtracted from each another and the software does not include this function. Instead two-dimensional slices through the image are being used to determine the difference between the highest and lowest points and whether this changes or remains constant over the 12 months. Further work will be required to fully analyse these samples making it time-consuming. The software generates the three-dimensional map from images so the precision quoted in terms of the height differences is due to the calculations and an exaggeration of the actual precision possible. Options for creating image stacks with other software are currently being explored.

Conclusion

The monitoring techniques used have allowed large volumes of data to be collected from the objects. However, the downside of this is the large amount of time required to process and analyse this data, often requiring additional software packages, e.g., to undertake MVA. Monitoring collections in these ways offers the potential to inform us of which environments cause damage in practice, instead of relying on the theoretical lab behaviour of new materials. Currently, adequate techniques are not available 'off-the-shelf' to undertake collections monitoring successfully and simply. Accelerated ageing has also been undertaken as part of this research, and a number of the monitoring techniques were applied in lab conditions to provide more detailed information. However, the lab samples were new and their response was more pronounced. As the same monitoring techniques were used to analyse the lab samples, the same time-consuming problem of data analysis was also incurred. Nevertheless, the project did demonstrate that had recommendations been made based only on results from the lab samples they may well have been overly restrictive when compared with the few changes recorded on the display objects.

Acknowledgements

References

[1] Erhardt, D., and Mecklenburg, M.F., 'Accelerated vs natural aging: effect of aging conditions on the aging process of cellulose', in Materials Issues in Art and Archaeology IV, ed. P.B. Vandiver, J.R. Druzik, J.L. Galván Madrid, I.C. Freestone and G.S. Wheeler, Materials Research Society, Warrendale (1995) 247–270.

[2] Mecklenburg, M. F., Tumosa, C. S., and Erhardt, D., 'Structural response of painted wood surfaces to changes in ambient relative humidity', in Painted Wood: History and Conservation. Proceedings of a Symposium Organized by the Wooden Artifacts Group of the American Institute for Conservation of Historic and Artistic Works, Williamsburg, Virginia, 11-14 November 1994 ed. V. Dorge, F.C. Howlett, The Getty Conservation Institute, Los Angeles (1998) 464–483.

[3] Mecklenburg, M.F., and Tumosa, C.S., 'Mechanical behavior of paintings subjected to changes in temperature and relative humidity', in Art in Transit: Studies in the Transport of Paintings, ed. M.F. Mecklenburg, National Gallery of Art, Washington D.C. (1991) 173–216.

[4] Canadian Conservation Institute, 'Environmental Guidelines for Museums – Temperature and Relative Humidity (RH) Vulnerable Objects' http://www.cci-icc.gc.ca/caringfor-prendresoindes/articles/enviro/vuln-eng.aspx (accessed 10 August 2012).

[5] AHRAE, 'Museums, galleries, archives and libraries', in ASHRAE Handbook – HVAC Applications, ed. M.S. Owen, ASHRAE

– American Society of Heating, Refrigerating, and Air-Conditioning Engineers Inc, Atlanta (2007) 21.1–21.23.

[6] http://www.hpl.hp.com/research/ptm/ (accessed 10 August 2012).

[7] http://www.lavision.de/en/techniques/digital-image-correlation.php and http://www.lavision.de/en/products/strainmaster-dic.php (accessed 10 August 2012).

[8] Luxford, N., Strlič, M., and Thickett, D., 'Change or damage? Using dissemination to encourage public involvement in conservation research'. Playing to the galleries and engaging new audiences: the public face of conservation, Colonial Williamsburg, U.S.A. 14–16 November 2011 (submitted).

[9] Richardson, E., Martin, G., Wyeth, P., and Zhang, X., 'State of the art: non-invasive interrogation of textiles in museum collections' Microchimica Acta 162 (2008) 303–312.

[10] Studer, J., 'Application of acoustic emission technique to limoges enamels for damage assessment', CeROArt, http://ceroart.revues.org/2569 (accessed 30 August 2012).

[11] Khennouf, D., Dulieu-Barton, J. M., Chambers, A. R., Lennard, F. J., and Eastop, D. D., 'Assessing the feasibility of monitoring strain in historical tapestries using Digital Image Correlation' Strain 46 (2010) 19–32.

Authors

Naomi Luxford is an AHRC/EPSRC Science and Heritage postdoctoral research fellow at the UCL Centre for Sustainable Heritage working on Change or Damage?
Email: n.luxford@ucl.ac.uk

David Thickett is Senior Conservation Scientist in the Collections Conservation team at English Heritage.
Email: David.Thickett@english-heritage.org.uk

Licence

What real museum objects can teach us about the influence of climate conditions

Paul van Duin

Abstract

The Climate4Wood research project will start in December 2012. Its aim is to provide guidelines for a more sustainable museum climate. Part of this project will be a museum study, to develop a better understanding of the influence of climate on decorated wooden panels. In anticipation of the start of the project, observations on furniture in the Rijksmuseum and Castle Amerongen are discussed to give direction to the museum study.

Climate4wood

When people are concerned about climate conditions, it is usually because they are worried by climate graphs, not because they observe damage. When one observes damage it is of course too late, but how much caution is necessary? To which extent can the strict climate specifications developed in the 1960s and 70s be safely relaxed? And once that is established, how can the conservation community be convinced that their objects are safe in those conditions?

Deciding on proper climate specifications for museum environments is a daunting task. Type and condition of objects, risk assessment, installation requirements, building physics, construction as well as running costs of any installation, and the impact of the energy consumption on the environment have to be weighed against each other. Most actors involved in the decision-making process are specialists within their own field, with usually lesser knowledge about the other factors. The way forward is for professionals from different fields to closely collaborate in research projects to develop an understanding of each other's expertise in order to better address the research questions. The Netherlands Science Foundation started a programme in 2010 called Science for Arts. This programme aims to develop and strengthen interchange between the research of universities and the museological field. NWO Science for Arts recently accepted a research proposal called Climate4Wood, developed by the Rijksmuseum, the Netherlands Cultural Heritage Agency and the Technical Universities of Eindhoven and Delft. The aim of the Climate4Wood project is to identify the relative humidity (RH) fluctuations that decorated wooden panels (panel paintings as well as furniture) can safely sustain and to develop rational guidelines for climate specifications in museums. Our project focuses on decorated wooden panels as this is a category which is regarded as being very susceptible to climate fluctuations. Conservators, conservation scientists and engineers will closely cooperate to develop a better understanding of the behaviour of panels and to predict more accurately under which circumstances damage might occur. The outcome of the project should help museums to become more sustainable by balancing the cost and preservation of the collection. The project has international partners, such as CATS/

National Gallery of Denmark and the Metropolitan Museum of Arts and is supported by a large international advisory committee.

The Climate4Wood research project, which will start on 1 December 2012, consists of a so-called museum study by means of a doctorate research position in conservation, combined with a material and mechanical modelling study through doctorate and post-doctorate research positions in engineering. The museum study will investigate the construction, materials and condition of a large collection of decorated wooden panels and how these have been affected by climate conditions. The results will be used as input for the modelling study, to model climate and age-induced stresses and deformations. A postdoc will determine and model the relevant non-linear elastic material properties.

This article will first describe how, in 2002, the Rijksmuseum decided on new climate specifications. This will be followed by various observations, in anticipation of the museum study, on real wooden museum objects, from my point of view as a furniture conservator.

Setting the climate specifications for the new Rijksmuseum

The Rijksmuseum experienced the challenge of setting climate specifications in 2002 when Bart van der Pot, the project director for the renovation of the Rijksmuseum asked the museum for the environmental specifications for the 'new' museum. In 2002, in the Netherlands, the climate specifications advised by the Cultural Heritage Agency were still strict: 52 % plus or minus 3 % RH, and a temperature (T) of 21 °C plus or minus 2 K [1]. Van der Pot argued that these specifications were impossible to achieve. RH sensors have errors of 1 to 2 % and would therefore be unable to adequately help to maintain such a strict climate. He warned that the climate installations would be extremely expensive and take up a large percentage of the building. The museum building would suffer from installing all the equipment and ducts, but also the building physics would be affected in due course, mainly because the humidity would cause condensation problems. In winter, the higher water content within the walls might freeze, resulting in damage to brickwork. The conservators felt that the objects might be at risk by broadening the specifications and the directors did not want to take that responsibility either. After lengthy discussions the stalemate was finally lifted by Van der Pot's suggestion to look at the actual climate data and its effect on the objects. The climate data showed that the relative humidity in the galleries varied between c. 65 % and 45 % and the conservators were not aware of damage that had visibly occurred. Damage to objects that had happened in non-climatised areas will be discussed below. Broader specifications were agreed upon that follow the seasons: in summer 54 % plus or minus 5 % RH with T of 23 °C plus or minus 2 °C and in winter 50 % plus or minus 5 % with T of 20 °C plus or minus 2 °C. The new specifications should be more realistic, resulting in a better controlled climate than before. It has to be admitted that not all conservators felt at ease with the new specifications. Some conservators fear that broadening the specifications might lead to larger fluctuations than before. Even when the actual climate would meet the new specifications they find 45 % RH risky. From April 2013, when the Rijksmuseum reopens, we will find out if the climate specifications are realistic and we will be able to monitor how the objects will react to the new climate.

The decision-making process in the Rijksmuseum was, of course, not an isolated event. Even before 2002, research indicated that the strict climate specifications that had been in use since the 1970s could be relaxed [2]. But even now the conservation community is not entirely convinced that climate specifications can be relaxed without putting their objects at risk [3]. Evidently, more research is needed to predict under which circumstances damage might occur. Wooden objects in particular show well-known kinds of degradation, such as shrinkage cracks and warping of wood. But do we know when this damage occurred and under what circumstances? And do we understand how this damage is related to the construction of the object, its material properties, its age and condition? All of these factors can vary, and the susceptibility to climate conditions will vary accordingly [4].

Damage observed in real-life

As mentioned above, no damage to the Rijksmuseum collection was observed in areas with a controlled climate. For many years, conservation studios were housed in the Teekenschool, a separate building with central heating, mobile humidifiers and single pane glass. In the Teekenschool, shrinkage damage occurred several times during cold wintery spells, with outdoor temperatures well below 0 °C and clear blue skies. Even humidifiers could not prevent the RH dropping below 30 %, as the water in the air condensed against the windows. Sometimes the RH dropped as low as 20 %.

During the winter of 1993 we treated the kitchen of the dolls' house of Petronella Oortman (Figures 1, 2) [5]. The rooms of that dolls' house are actually wooden boxes, open at the front. The walls, floors and ceiling are made of oak and pine panels, c. 5 mm thick. The kitchen walls are made of 5 mm-thick pine, on to which ceramic tiles of 10 x 10 cm were glued. In the 300 year-lifespan of the dolls' house the pine panel of the left wall

Figure 2. The left wall of the kitchen of figure 1 before conservation. The pine panel has warped, causing damage to the tiles. After conservation, the panel moved again during a week with an RH below 30 %

had shrunk and warped, causing the tiles to crack. Our ceramics conservator Isabelle Garachon removed the tiles, and glued, filled and retouched the cracks. The pine panel was straightened by us and the tiles were re-glued against the pine. As I find it of particular importance to preserve the original construction of furniture, I managed to persuade Isabelle that we would not use an alternative method to attach the tiles to the wood. Whilst the kitchen was still in her studio, we enjoyed an old-fashioned Dutch winter with skating on the Amsterdam canals. During a week with heavy frost, hairline cracks appeared along the repairs to the tiles. Obviously this was caused by the shrinkage of the pine, which put pressure on the repairs. We decided to remove the tiles and to adhere them to a 1 mm-thick aluminium perforated sheet which was fixed to the pine wall allowing some movement of the wood without transferring this to the tiles. Although it was clear that the low humidity caused the old as well as the new damage, the other tiled walls of the kitchen never suffered damage, and did not need conservation. Also, the floor, which consists of 5 mm-thick oak panels, onto which a 5 mm-thick marble slate is glued, remains intact. It would be interesting to establish why some tiled walls suffered damage whilst others survived well.

During a cold winter in 1991, a seventeenth-century marquetry door of the recently acquired cabinet, then attributed to Pierre Gole and more recently to André-Charles Boulle, developed a hairline crack (Figure 3) [6,7]. This c. 30 cm-wide door is constructed of two oak boards, with cleated ends and is veneered on two sides with marquetry. The RH was between 20 and 30 %, and outside temperatures were well below 0 °C for a week. This terrible accident was fortunately an exception and most furniture in the conservation studio did not suffer during these dry conditions. In milder weather we never observed any damage. These observations clearly indicate that a period of several days with an RH below 30 % is highly dangerous, but fortunately not to all kinds of furniture.

Comparison of the condition of similar objects

During a masterclass in the Rijksmuseum in 2010, the construction of 16 pairs of late-seventeenth century flat oak doors veneered on both sides with marquetry was investigated (Figure 4) [8]. All doors consisted of vertical boards, restrained by horizontal elements. Most doors were constructed of vertical oak boards with cleated ends. Dimensions of boards and cleated ends varied considerably. Other construction elements varied, one door was hollow, another door consisted of four panels set in a framework and one door had vertical boards into which short horizontal blocks were incorporated. The cabinetmakers were undoubtedly experimenting with construction methods that aimed at keeping the door flat and without shrinkage cracks. Although there were many variations in the construction of the doors, all had shrinkage cracks and some were warped to some extent. The shrinkage percentage seemed to be very similar, mostly around 1 %. Shrinkage cracks were mostly joints which had come apart. Apparently the stress led to glue-failure instead of actual splitting of boards. The question arises if the cracks only occurred due to ageing of the glue. The glue had survived well in areas where there was less stress, for instance the glue between veneer and oak substrate, where veneer was applied in the same direction as that of the oak. The vertical boards of the doors with cleated ends showed slightly less shrinkage where they were joined to the cleats. This can be explained by the restraint that the cleats provided. Further away from the cleats, in the middle of the doors, the vertical cracks between the boards widened. It is very interesting that the cleats cause cracks between the vertical boards, but that the damage near the cleats was less than in the middle of the door. The doors that had received conservation treatments in the past 30 years were still in good condition. New damage, if there was any, consisted of hairline cracks or some extra warping. Although many panels in furniture

Figures 5a and 5b. Front and back of the left door of a cabinet dated 1607. Oak, h. 140 cm, w. 55 cm, d. 3 cm, Netherlands. Rijksmuseum, BK-16071. The oak is all radially cut. The tongue and groove joints of the back panels are partly exposed at the top and bottom. Small cracks are visible in the lower right corner and the top left corner

have shrinkage cracks, usually with a shrinkage percentage of around 1 % as was observed during the masterclass, we do not know when these cracks occurred and if shrinkage is a continuing process. The Climate4Wood museum study will inspect and record a great number of panels, to see what variation in shrinkage there is, and how this relates to the type of construction, the age and materials used.

Conservators mostly deal with damaged objects, but we can learn much from objects or parts of objects which have survived well. For a presentation on furniture panels for the Getty Symposium in 2009 'Facing the Challenges of Panel Painting Conservation: Trends, Treatments, and Training', several early seventeenth-century oak panels were compared [9]. Whereas most doors of the cabinets had the kind of shrinkage cracks that one would expect, a relatively thin door from an oak cabinet dated 1607 hardly showed any damage at all (Figure 5). A large part of the 7 mm-thick panel was covered with equally thin mouldings. These were glued onto the panel, covering about 30 % of the panel with cross grain oak. This might indicate that this kind of construction can withstand climate fluctuations better. An explanation for this can be that the glue bond is much larger and therefore stronger and that apparently the wood is flexible enough to absorb the stress. This cabinet shows that the early seventeenth-century craftsmen were masters in selecting wood with the best material properties and also knew how to glue the door so well that most of the mouldings still remain firmly attached after 300 years. The Climate4Wood project will seek to answer in more depth why some early seventeenth-century doors have smaller shrinkage cracks than others.

Comparison with old photographs

Jan van Mekeren is a famous Dutch cabinetmaker from the seventeenth century. Cabinets attributed to him survive in various large museums, probably with good environmental controls, such as the Victoria & Albert Museum, Metropolitan Museum of Art and Rijksmuseum, but also in Castle Amerongen, a seventeenth-century house with no environmental controls. The Van Mekeren

Figure 7. An exploded view of the construction of the left door of the cabinet of Figure 6. Google Sketch up drawing made by Iskander Breebaart. Rijksmuseum
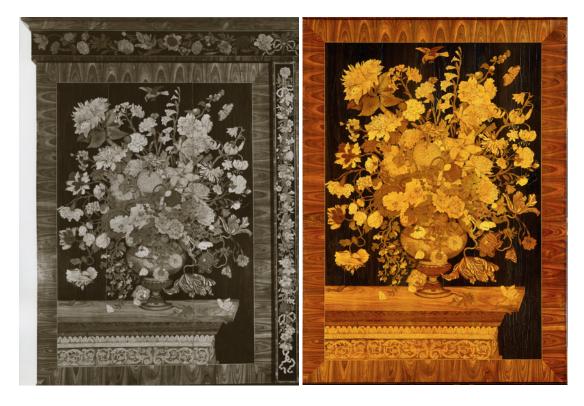
Figure 6. Cabinet on stand, attributed to Jan van Mekeren, Amsterdam, ca. 1695. Oak veneered with ebony, kingwood, and marquetry of indigenous and tropical veneers. Rijksmuseum, BK-1964–12

cabinets of the Rijksmuseum and Castle Amerongen were studied as part of a research project into climate conditions for furniture and panel paintings that the Dutch Cultural Heritage Agency, Rijksmuseum, TU Eindhoven, University of Amsterdam and Kasteel Amerongen started in 2009. The Van Mekeren cabinet in the collection of the Rijksmuseum was treated in 1995 (Figure 6) [10, 11]. Each door is constructed of two 8 mm-thick oak panels, glued onto either side of a frame, five horizontal stretchers and 30 glue-blocks (Figure 7). Each panel is made from three vertical boards. The doors are completely covered with marquetry of various veneers, with a background of ebony veneer. The doors had severe cracks, which distorted the marquetry design. Around the large cracks, the glue bond between the boards and the frame and stretchers had failed. The marquetry was frail along the edges of the cracks and new cracks were visible next to a previous filling, c. 0.5 mm wide.

Conservation was carried out for aesthetic reasons as well as to prevent further loss of marquetry. Before the treatment started, the cracks were photographed in detail. During an earlier research project of the Netherlands Cultural Heritage Agency (RCE), Rijksmuseum and University of Amsterdam, Bart Ankersmit from the RCE suggested using old photographs as a reference. The comparison between detailed black and white photographs taken in 1963 prior to the acquisition of the cabinet, with the photographs taken prior to the conservation treatment showed that the condition of the marquetry had not visibly deteriorated between 1963 and 1995 (Figure 8). The shrinkage crack next to the filling, for example, already existed. Cracks had not become longer, and new cracks had not appeared. Also hairline cracks in the ebony veneer remained unchanged. As the cabinet had been in the climate-controlled Rijksmuseum environment, albeit probably not as strict as 52 % plus or minus 3 % RH, perhaps this is not a real surprise. We assume that the climate was between 45 to 65 % RH, and further research is necessary to reconstruct the historic climate conditions more accurately. Unfortunately, data of

the climate before conservation in 1995 have not been preserved. Interestingly, the condition of the Van Mekeren cabinet in Castle Amerongen, housed in a very different environment, also seems to have been stable in the last decades. The construction of the cabinet is identical to that in the Rijksmuseum. The condition of the doors is also very similar to that of the Rijksmuseum cabinet before conservation. Comparison of the condition of the Amerongen doors in 2011 with photographs from 1964 showed that neither the large cracks caused by the shrinkage of the oak construction have propagated, nor the hairline cracks in the ebony veneer. It is difficult to judge from the photographs if the large cracks have changed in width. Around the large cracks, the boards are partly loose from the frame and stretchers. This might imply that those parts of the boards are less restricted and thus might be able to withstand larger fluctuations. The Climate4Wood project will use imaging techniques in situ to determine to what extent the boards move.
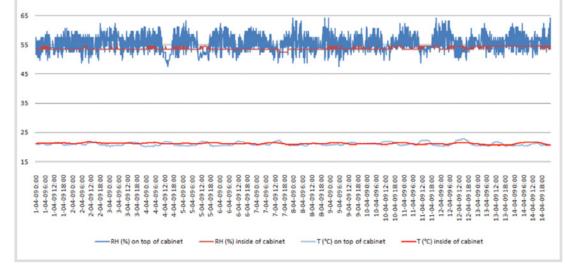
Conservation treatments

The Van Mekeren cabinet in the Rijksmuseum was extensively treated in 1995. The original construction of the doors was taken apart in order to move the boards against each other to close the cracks. Subsequently, the original construction was re-glued. The movement of the front and back panel is now once again fully restrained by the horizontal elements of the frame, stretchers and glue blocks inside the hollow doors. After the conservation treatment the cabinet was put on display again and its condition is still in good order. The RH in the present position, where the cabinet has been since January 2004, fluctuates between 50 % and 60 % (Figure 9). One may conclude that possible stress to the construction due to the fluctuations in humidity is absorbed by the construction.

As mentioned above, the condition of the Amerongen cabinet seems to be stable and conservation treatment is not deemed necessary at present. An interesting research question is whether the Amerongen cabinet can be treated in the same way as the Rijksmuseum cabinet, given the climate in an historic house. Which climate fluctuations can a fully re-glued and therefore restrained construction withstand? In this respect it is interesting to note that on both cabinets the joints between the boards have not fully cracked in the part where the front is covered across the grain with the veneer of the marquetry table-top. The higher amount of restraint provided by the cross-grain veneer has acted in the same way as the cross-grain mouldings of the cabinet mentioned above, dated 1607.

Climate inside cabinets

The interior of a cabinet has a very stable climate, undoubtedly because the wood around it acts as a buffer (Figure 9). Therefore, one would expect less damage caused by climate fluctuations in the inside than on the exterior of a cabinet. Surprisingly, this does not appear to be true. The back of the Van Mekeren doors for instance, has the same shrinkage percentage as the front. The shelves have also shrunk and even the drawers, which fit into a wooden compartment, show shrinkage cracks in the drawer-bottoms. The same phenomenon is observed in other cabinets. It is not unusual to come across cracks in drawer-bottoms which have

Figure 9. Climate graph from 1 July 2009 to 14 July 2009, Rijksmuseum Gallery 5. Sensors were placed on top of the cabinet (blue lines) in Figure 6, and also inside the cabinet (red lines)

been filled in the past and have since developed cracks next to the filling material. An explanation for this shrinkage is not apparent, and how and when the damage occurred are valuable research questions. Does wood in the stable climate conditions that a cabinet interior provides indeed shrink to the same extent as the exterior of a cabinet?

Conclusion

Monitoring objects in relation to climate conditions has led to broader climate specifications. Further research is necessary to decide on a sustainable museum climate. New shrinkage cracks were only observed in very dry conditions with an RH below 30 % for a period of a week, but not all furniture is damaged in those conditions. Shrinkage cracks in furniture are often joints which have come apart, this means that not just the properties and ageing process of wood, but also those of glue should be taken into consideration. Wood is less prone to shrinkage when it is restrained by cross-grain wood, such as mouldings, veneer and near cleats. This restraint has to be included in climate research, and should be studied for the stability it can provide as well as the damage it may cause. Even when wood is in the relatively stable climate of the interior of a cabinet, it seems to show the same shrinkage percentage as the exterior wood. To decide on safe climate specifications for furniture, one has to take into account the whole construction and the properties of every material used.

Acknowledgements

Thanks are due to the Climate4Wood research team: Bart Ankersmit, Roger Groves, André Jorissen and Henk Schellen, to Lodewijk Gerritsen of Castle Amerongen and to my colleagues Robert van Langh, Iskander Breebaart and Gert van Gerven.

References

[1] Jütte, B.A.H., Richtlijnen voor het bouwen of verbouwen van ruimten met een museale bestemming, CL-informatie (17) Amsterdam (1994).

[2] Mecklenburg, M. F., Determining the Acceptable Ranges of Relative Humidity and Temperature in Museums and Galleries, Smithsonian Museum Conservation Institute, Washington (2007).

[3] Craft, M., Rethinking the Museum Climate, AIC Blog, 23 April 2010. http://blog.conservation-us.org/blogpost. cfm?threadid=2227&catid=175 (accessed 19 September 2012).

[4] Michalski, S., 'The ideal climate, risk management, the ASHRAE chapter, proofed fluctuations, and towards a full risk analysis model', in Experts Roundtable on Sustainable Climate Management Strategies, The Getty Conservation Institute, Tenerife (2007). http://www.getty.edu/conservation/our_projects/science/climate/ paper_michalski.pdf (accessed 19 April 2013).

[5] Pijzel-Dommisse, J., Het Hollandse Poppenhuis, Interieurs en Huishouden in de 17de en 18de eeuw, Amsterdam, Zwolle: Rijksmuseum, Waanders (2000) 308–309.

[6] Duin, P. van, 'Het Gole kabinet. Constructie, conservering en restauratie', Bulletin van het Rijksmuseum 41 (1993) 96–123.

[7] Baarsen, R.J., Seventeenth-century Cabinets, Amsterdam/ Zwolle, Rijksmuseum/Waanders (2000) 56–62.

[8] Duin, P. van, 'The construction of flat decorated doors of Dutch seventeenth-century cabinets. Report of a master class', in Restoring Joints, Conserving Structures. Tenth International Symposium on Wood and Furniture Conservation, Amsterdam, 8–9 October 2010, ed. M. Vasques Dias, Stichting Ebenist, Amsterdam (2011) 121–143.

[9] Duin, P. van, 'Panels in furniture: observations and conservation issues', in Facing the Challenges of Panel Painting Conservation: Trends, Treatments, and Training, Getty Centre, 17–18 May 2009, ed. A. Phenix, S.A. Chui, Sue Ann, The Getty Conservation Institute, Los Angeles (2011) 92–103.

[10] Breebaart, I., 'The conservation of two late-seventeenth-century cabinets-on-stand', in Restoring joints, conserving structures. Tenth International Symposium on Wood and Furniture Conservation, Amsterdam, 8–9 October 2010, ed. M. Vasques Dias, Stichting Ebenist, Amsterdam (2011) 82–93.

[11] Baarsen, R., Furniture in Holland's Golden Age, Rijksmuseum, Amsterdam (2007) 40–42.

Author

Paul van Duin is head of furniture conservation at the Rijksmuseum Amsterdam. He is also advisor to the Getty Panel Paintings Initiative. In 2011, he organised an expert meeting with NWO and Getty to define a research agenda for the structural conservation of panel paintings and related works of art. Email: p.van.duin@rijksmuseum.nl

Image credits

All images © Rijksmuseum

The Oseberg ship. Long-term physical-mechanical monitoring in an uncontrolled relative humidity exhibition environment. Analytical results and hygromechanical modeling

Paolo Dionisi-Vici, Ottaviano Allegretti, Susan Braovac, Guro Hjulstad, Maria Jensen and Elin Storbekk

Abstract

A continuous monitoring system was installed on the Oseberg ship, a large Viking Age archaeological wooden object (oak), in order to determine the material response to the uncontrolled conditions at the Viking Ship Museum, Oslo, Norway. Four areas have been monitored since July 2009, two boards on the ship and two samples free to deform (recent oak and a sample removed from the ship). Results, reported for 2010/11, showed that extent of deformation is related to extent of restraint. The greatest extent of strain (warping) was found for the recent oak sample, followed by the unrestrained archaeological sample. Of the restrained samples, that with greatest loading showed least strain.

Introduction

Museums worldwide are currently engaged in a lively debate on gallery climate conditions, namely acceptable levels of relative humidity (RH) and temperature (T) and acceptable fluctuation levels. The discussion on appropriate climate is of prime relevance to the conservation staff at the Museum of Cultural History (KHM) in Oslo since renovations to the Viking Ship Museum (VSH) are planned. The Viking Ship Museum, administered by KHM, is dedicated to the display of the Norwegian Viking Age ship burials from Borre, Tune, Gokstad and Oseberg excavated in the late nineteenth and early twentieth centuries.

The collections on display are mainly of archaeological wood. The Viking Ship Museum was built in three stages (1926, 1932, 1956) without an active ventilation system. No major renovations have been carried out since then. Smaller objects are displayed in climate-controlled display cases; however the three large ships and several other wooden archaeological objects are displayed without enclosures. It is a listed building, meaning that any building changes must be approved by the national antiquary.

In light of the planned renovations, the conservation staff must decide whether the climate conditions (RH and T) at the Viking Ship Museum should be improved or left as they are; that is, should we opt for the installation of a full or partial actively-controlled climate system, or should we trust that the objects have become acclimatised to the existing climate?

Today many agree that the decision to improve a non-ideal climate by the installation of active control systems must balance collection preservation needs with energy consumption and the personnel resources required to maintain it, as well as considering

the potentially disastrous consequences when such a system fails [1, 2]. Maintaining the status quo may outweigh the potential benefits of an active system in buildings that are not climate-controlled.

The climate history of an object has become recognized as an important factor to consider regarding appropriate climate. The relatively recent European Standard for evaluating climate in museums and galleries for hygroscopic materials maintains that exposure to the same environment over many seasonal cycles may proof the objects, making them less vulnerable to the development of new climate-induced damage [3]. Before the assessment method described in the Standard may be applied to a particular collection, preservation professionals must undertake systematic investigations of the objects in question to ascertain that existing climate conditions are not causing new damage, and thus are acceptable. The authors read this as an explicit statement basically saying we have to start to think of the specific collection environment and not blindly rely on general recommendations. The Standard may also be interpreted as an implicit appeal to intensify systematic research on the effects of climate on hygroscopic materials; otherwise how will we be able to 'evaluate' whether climate-related damage has occurred or not? Which methods should be used to evaluate damage? Which parameters should be measured?

Finding the appropriate climate range in practice

The Viking ships have been subjected to an uncontrolled climate since their installation in VSH in 1926 and 1932. The display area is therefore influenced by seasonal changes in RH, which rise above 70 % in summer, at times up to 80 % RH (May to October) and drop
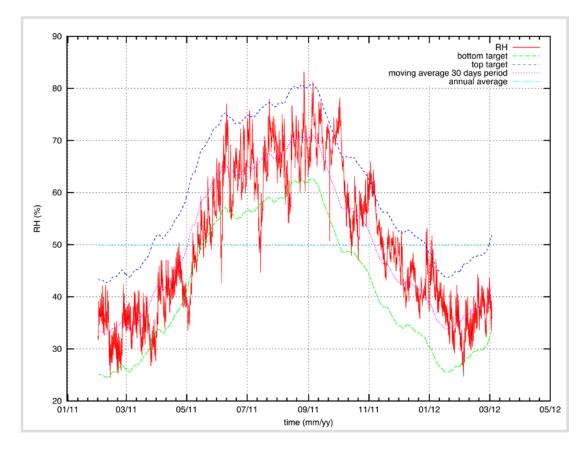

Figure 1. The climate (RH and T) measured in the Viking Ship Museum between 2011 and 2012. Bottom and top target levels were calculated according to the procedure given in the EN 15757:2010 standard [3]

below 30 % in winter (November to April). Annual temperature ranges from 9 to 25 °C, and can rise to 28 °C in summer for short periods.

Relative humidity fluctuations in summer range from 10 % in half a day to 20 % in 1.5 days and in winter are approximately 10 % over the course of half a day to one day. Figure 1 illustrates the climate from January 2011 to March 2012, calculated according to the procedure given in the European climate standard, if we assume that the objects openly displayed are proofed [3]. The climate data is shown for a three-year period to demonstrate the rather regular climatic cycling between winter and summer seasons in the museum.

When conservation staff at KHM attempted to visually examine the condition of the archaeological wooden ships to determine whether the regular climate conditions had in fact proofed them, we found that it was difficult to assess whether existing cracks in the wood were of a recent nature, were the result of older acclimatization processes or whether they had originated from post-excavation drying stresses. We could, however, see relatively recent damage in the wood due to inadequate supports: sagging between the points of support. Although it is known that dynamic short- and long-term RH and T cycling can contribute to permanent plastic deformation of wood under loaded conditions [4, 5], we were unsure whether the material itself, in areas where there was not much gravity loading, had become proofed.

Thus, there are two aspects to consider about the climate conditions at the Viking Ship Museum:

1. The effect of the climatic variation on the material of the ships;
2. The long term effect of the fluctuating climate on permanent deformation of the lower parts of the object under loading from gravity, as well as from the weight of supporting upper boards.

Preliminary results for the first aspect will be described in this paper. The second issue will be addressed in a future project.

The monitoring project

Because plans for upgrading the Viking Ship Museum have been known for several years, conservation staff tried to anticipate the information which architects and engineers would need when the time came for starting the renovation process, such as climate specifications for the collection. There is little information available in the literature about wood-moisture relations for archaeological wood. This is probably because archaeological wood's response to climate fluctuations can vary considerably, depending on its condition and how it had been treated prior to drying [6]. The authors were therefore unsure to what extent the existing literature on non-archaeological/un-degraded wood could be used to assess our ships with regard to their response to fluctuations in T and RH.

Thus, in March 2009 a project was initiated at the Viking Ship Museum to monitor the effect of the uncontrolled display environment on the dimensional changes in the wood of one openly displayed archaeological wooden object, the Oseberg ship (Figure 2). We were interested in understanding how current seasonal

and short term T and RH fluctuations affect dimensional changes of the wood making up the ship to eventually determine which fluctuations would be most important to avoid. We were also interested in seeing to what extent the data from the Oseberg ship was comparable to the information found in the literature (on un-degraded wood).

The Oseberg ship, dating from c. 820 AD [7], is one of the most important discoveries of the Viking age period in Norway. The fact that it consists of 90 % original material makes it a unique find. The ship is 21.5 m long, built with radially cut 2.5 cm thick oak planks and is 5 m at its widest. Originally the ship was built upwards from the keel in the 'clinker' type of construction, where boards are attached to each other in an overlapping fashion.

In 1904 the waterlogged wood was conserved with linseed oil and creosote and allowed to air dry. In 1957 the surface was coated once again with linseed oil diluted in white spirit [8]. The ship was reconstructed in the same clinker fashion from over 2000 pieces, using both original and modern rivets, as well as screws, nails, adhesive and new wood. Steam had been used to shape the boards during reconstruction. It is currently supported at points placed at regular intervals along the lower boards of the ship. The support system is undergoing improvement.

The measurement campaign on the Oseberg ship started in July 2009, and is still ongoing. Due to the amount of data, the period from January 2010 to December 2011 will be presented here. To our knowledge, this is the first example of long term hygro-mechanical [9] monitoring on an archaeological wooden artefact. The Oseberg ship can be considered representative of the three ships on display, since all ships are made of heartwood oak, and it was treated in the same way as the Gokstad ship (the Tune ship was not treated at all).

Figure 2. The Oseberg ship, openly displayed in the uncontrolled exhibition environment

Figure 3. The **dendro oak** sample with the deformometric kit mounted on it. The two transducers making up the Deformometric Kit (DK) are each connected to a datalogger, which also monitors RH and T

The technique used to measure dimensional changes on the Oseberg ship, described in more detail in the Methods section below, establishes a direct relationship between the hygro-mechanical response of the wood to changes in its surrounding climate and involves continuous monitoring. This minimally-invasive method has been successfully implemented on different types of works of art in various museums, and is a useful tool that gives solid experimental data for further analysis [10]. This paper presents a work in progress. Further developments need to be established.

Materials and methods
Materials

Four samples are involved in the monitoring project: two planks on the Oseberg ship and two samples free to warp, one of which is a sample taken several years ago for dendrochronological dating (**dendro oak**) and the other of recent oak (**fresh oak**). All four samples are of nearly radially cut oak heartwood.

The **dendro oak** sample had been cut from the lower part of the reconstructed ship across the entire width of the board in the early 1990s (Figure 3). Its dimensions are 30 x 5 x 2.4 cm (length x width x thickness), with the grain direction across the short side.

The Oseberg boards (**upper ship, lower ship**) have a thickness of c. 25 mm. The width of the boards is c. 300 mm.

As already mentioned, the Oseberg wood was previously treated with linseed oil and creosote. Examination of cross-sections of samples from the ship showed that the surface coatings penetrated the wood minimally across the grain, up to about 3 mm. The average mass density of the Oseberg oak samples is 0.605 g/cm^3 [11].
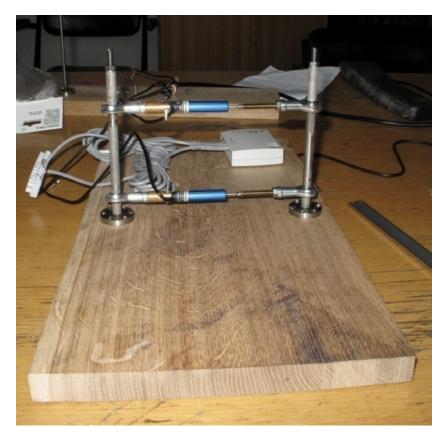
The fourth sample is of un-aged seasoned oak (41 x 22 x 2.2 cm, mass density 0.632 g/cm^3), and is termed **fresh oak** in the study. It has not been surface-treated.

The two smaller samples (**dendro oak, fresh oak**) had their end-grain sealed by aluminum foil tape in order to eliminate water adsorption in this direction, since the boards measured in the ship do not have exposed end-grain.

The measurement system

The Deformometric Kit (DK) is made up of two linear displacement sensors which are set up parallel to each other. The system is screwed directly into the sample. The parallel arrangement of the transducers allows for the use of basic geometrical equations to calculate different parameters from the data, including both in-plane and out-of-plane deformation [10].

The transducers used in the kits have a maximum displacement of 10 mm. The DK is approximately 150 mm in total length. As there is a linear relationship between the transducers' output voltage (0 to 2.5 V) and displacement (0 to 10 mm), the volt signal can be easily converted to mm by a simple calibration step, allowing a resolution of 10 µm/digit.

The two transducers making up the DK are each connected to a channel in the 4-channel HOBO data logger. The remaining two channels in the logger record RH and T. The sample rate is 15 minutes. The loggers are manually downloaded and the data are transferred into spreadsheets.

Set-up of the measurement campaign

Four kits are used in the measurement campaign: two installed directly onto ship boards that are partially restrained by rivets and nails, but which are not in direct contact with the exterior support posts (**upper ship** and **lower ship**) and two installed on samples (Figure 3, 4) which are free to deform (**fresh oak, dendro oak**). The unrestrained samples were placed in the ship after the DK was installed.

The **lower ship** board carries more of the weight of the ship than the **upper ship** boards, since it is located lower down in the structure. The **lower ship** board is also aligned more parallel to the plane of the floor than the **upper ship** board, and is thus more affected by gravitational forces.

The DK was installed across the grain on the nearly radially cut oak planks on crack-free, knot-free areas of the planks (as far as this was possible).

We have chosen to present data from January 2010 to December 2011. Results are expressed as % cupping arc length Δ across the width of the board. Measurements are reported for the concave side of the samples.

Results and discussion
Analysis of the data

The displayed values have the goal to represent the magnitude of the phenomena involved and cannot be extrapolated as characteristic values, directly comparable to other values that have been proposed in the literature [12, 13]. Though the quality
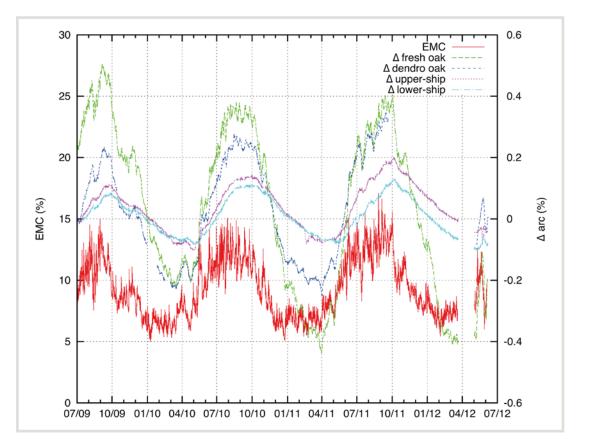

Figure 5. Percent strain across the width of the boards and EMC plotted vs. the timeframe 2009/12

of the measurements has been carefully verified, filtering out data that were disturbed by connection problems (as visible on the charts), the setup is not standard because of the constraints for the installation posed by the ship. The analyses presented here focus on the trends of the response of the chosen samples, which are obviously limited if considered in terms of an experimental population. Nevertheless, this is an aspect of the challenge of facing monitoring problems on real objects and, at this stage of the work, the results can be considered valid as a support for specific choices.

Generally, the response of the restrained samples is visibly different in relation to both sample type (recent oak vs. archaeological oak) and to the extent of constraint of the wood. The extent of % cupping arc length Δ is shown in figure 5 for each sample. Results are also summarized in table 1. The values used for equilibrium moisture content (EMC) were calculated using the Hailwood-Horrobin equation, converting each couple of measured RH and T in the corresponding EMC value [14]. The choice of using the Hailwood-Horrobin equation was based on the known assumption that wood also changes its moisture content (MC), even if in a smaller amount, under temperature variations at constant relative humidity values (Figure 6).

The adopted parameter (EMC) takes a snapshot of the potential MC that a wooden sample would achieve in stable conditions but, as already proposed in a previous paper [15], it can be used as a synthetic parameter involving both temperature and relative humidity in a single, physically- and wood-related value.

Considering the previously described wide temperature fluctuations in the exhibiting environment, the potential loss of information deriving from using only the relative humidity parameter makes it worth using this approach. The Hailwood-Horrobin equation has been adopted because of its widely verified reliability, even if the authors are aware of the need for specific isotherms for this particular material. The need for more species-related specific isotherms is also declared in a recent paper by other authors [16].

Dendro oak vs. fresh oak

There were significant differences in the climate response of the **dendro oak** sample relative to the **fresh oak** sample. Our measurements showed that although both samples followed a

Table 1: Measured strain range is given as per cent values. Overall climate conditions in the exhibition hall at VSH between January 2010 and December 2011 had a temperature range between 9 and 27 °C and RH between 22 and 83 %
* missing data from period 1/1/2010 to 25/1/2010, 16/2/10 to 3/3/2010, 23/9/2011 to 31/12/2011 – only 1 winter (2010)
** missing data from period 4/4/11 to 3/5/11

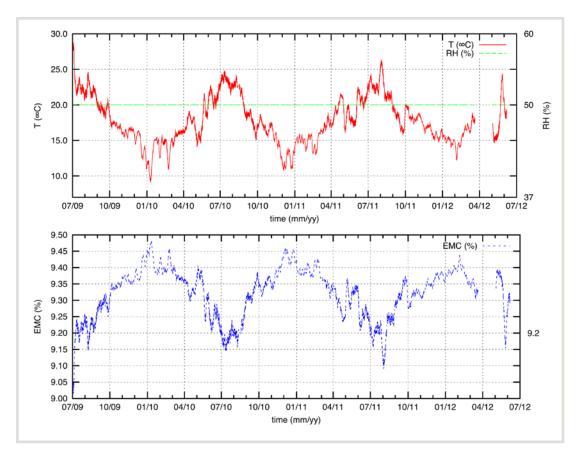|		fresh oak	dates fresh	dendro oak*	dates dendro	upper Ship**	dates upper	lower ship	dates lower
Max swelling, min shrinkage and total % strain	max	0.404	13.09.11 17:20	0.347	14.9.11 18:22	0.200	04.10.11 18:19	0.130	04.10.11 18:16
	min	-0.439	31.03.11 08:18	-0.252	01.4.11 03:03	-0.102	29.04.10 02:23	-0.083	01.5.10 09:08
	Δ %	0.843		0.599		0.302		0.213	

Figure 6. The potential EMC variations under hypothetically stable RH and temperature fluctuating in the experimental range

similar trend, the maximum strain across the width of the boards for instance, is smaller in the **dendro oak** sample (0.605 %) than that found in the **fresh oak** sample (0.850 %). Our measured values are much greater than those reported by Klein and Bröker [13] but are similar to those reported by Brewer and Forno [12].

Klein and Bröker measured 0.2 % and 0.15 % strain across the grain in 15 mm thick radially cut **fresh oak** and aged oak (not archaeological) respectively, when the RH increased from 55 to 85 %. They attributed the difference between fresh and aged oak to differences in the density of the two samples they measured. Brewer and Forno measured a 0.69 % strain in the unrestrained part of a 3.3 mm thick cradled panel made of radially cut oak (unaged) when the RH was increased from 33 % to 72 %. They also measured 0.47 % strain in an uncradled panel (unaged wood) when RH increased from 29 % to 80 %. The strain values in the latter study corresponded better to our **dendro oak** sample, while strain values for the **fresh oak** sample were much higher than in either study. The variation in results in the two studies compared to ours may be due to several factors: the extent of seasoning of the **fresh oak** sample or the measurement systems used, in addition to the fact that the **dendro oak** is chemically and structurally more deteriorated than fresh wood.

Chemical analyses of the Oseberg oak showed that it is highly depleted in both hemicellulose and amorphous cellulose, which would theoretically make it less polar than fresh wood; the lignin is more oxidized than that found in **fresh oak**, making it more polar than that found in **fresh oak** [17]. Modulus and strength measurements in the grain direction showed that Oseberg oak had between 15 to 30 % of the bending strength and about 20 % of the modulus of elasticity compared to that of **fresh oak** [11].

Another factor to consider when comparing the **fresh oak** sample with the **dendro oak** sample is the treatment received by the Oseberg wood (linseed oil and creosote). To what extent does this surface treatment affect our results? It is difficult to answer this question without further analysis of the data, but when considering short-term fluctuations in RH, the surface treatment will most likely buffer the wood to some extent, however for long-term fluctuations (summer vs. winter) we observed that the **fresh oak** and **dendro oak** samples follow the same pattern.

**Unrestrained (dendro oak) vs. restrained samples
(upper ship and lower ship)**

Relative to the **dendro oak** sample, the maximum extent of % strain from the restrained samples were significantly smaller. The extent of maximum strain for the **upper ship** was 0.302 %, while that for the **lower ship** was 0.213 % (Table 1). The difference in response of the restrained samples was expected when compared to **dendro oak**, since they cannot freely respond because they are riveted into place.

What does this mean?

If we consider the threshold value of 0.4 % strain as the average yield point for un-degraded wood (when deformation becomes permanent) we can see that the measurements for both **fresh oak** and **dendro oak** samples go beyond this value (0.599 % strain for **dendro oak**). However, the strain at which the yield point occurs for the **dendro oak** may be quite different from 0.4 %. We must also evaluate whether strain hardening has occurred in a similar way as it would for fresh wood. Strain hardening of wood is the phenomenon observed after climatic cycling, where permanent
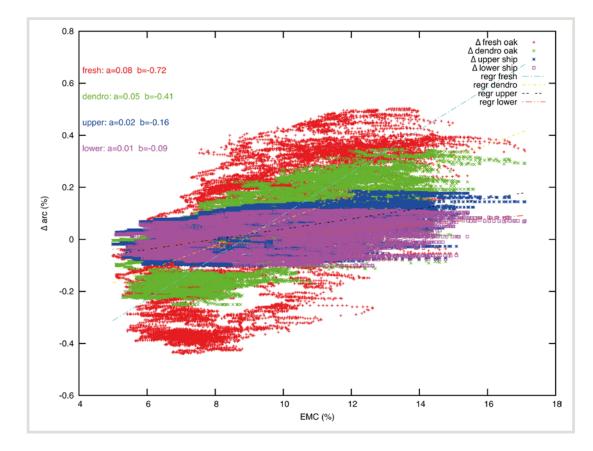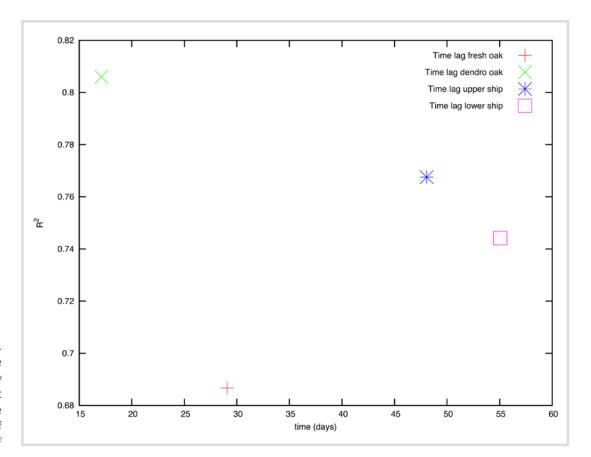

Figure 7. The plot of % strain for each sample vs. EMC for the period 2010/11. Linear regression was calculated without taking into account the delayed response time

(plastic) deformation occurs at a higher level of strain [18]. The presence of existing cracks must also be considered for the archaeological samples as they may contribute to the alleviation of the absorbed stresses, without necessarily affecting the dimensions of the gross sample.

Estimating response time of the wood to climatic variation

The slope of the linear regression undertaken for each sample vs. EMC estimates their different hygro-mechanical reactivity magnitudes (Figure 7). The greater the slope of the regressed linear equation, the greater the warping sample response to climate variations [19]. The slopes obtained using this analytical tool show clearly the different magnitudes of reactivity of the samples: the **fresh oak** has the highest reactivity magnitude, as expected, followed by the **dendro oak**, at a slightly lower level. Both the **upper ship** and the **lower ship** have much lower slopes, with the **upper ship** having a slightly higher value. This difference can reasonably be related to the different constraint level.

The slope found for the **dendro oak** sample is about three times greater than those for the **upper ship** and **lower ship**. Since the material is reasonably similar in all samples, the differences in % strain could suggest the accumulation of stress due to constraint in **upper-** and **lower ship** samples. Figure 5 shows that the response of the wood samples to seasonal climate fluctuations are significantly delayed. By maximizing the coefficient of determination (R^2) of the sample's response relative to EMC, response time can be estimated. The estimated response times for each sample (as shown in figure 8) may then be used to generate a new scatter plot (Figure 9) which takes into account the response delay parameter, decreasing data dispersion. While the delay
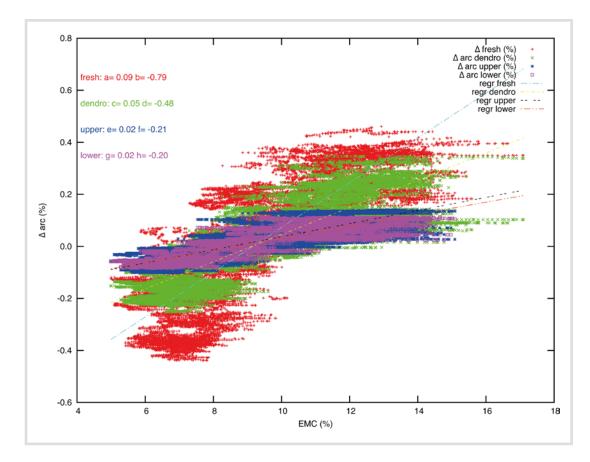
Figure 9. The plot of % strain for each sample vs. EMC for the period 2010/11. Linear regression was calculated by taking into account the delayed response time

values obtained for the archaeological samples are very consistent, according to the different constraint level, it is unclear why the **fresh oak** delay is higher than the **dendro oak**.

Conclusion

For both in-plane and out-of plane deformations, greatest changes were observed in the **fresh oak** followed by the **dendro oak**. The **upper ship** showed a greater extent of % strain than that measured in the **lower ship**. The results demonstrated that the extent of restraint affects the response, which was expected. The **fresh oak** sample was very reactive, showing large variations in % strain.

Has the material making up the ship stabilized after all these years in the same conditions? Has the object been proofed after being exposed to repeated annual cycling? An understanding of the general trend will be evident as we continue to monitor changes over the years.

A further experimental setup has been designed and is planned to be implemented in order to determine the magnitude of forces absorbed by the restrained samples in the ship. In this way, long-term hygro-mechanical effects of absorbed stresses in structural elements can be better understood. These data will eventually be used to validate a Finite Element Model aiming to describe the hygro-mechanical behavior of archaeological wood.

Acknowledgements

planning and installation phases of the monitoring system. The authors would also like to thank the reviewers for their helpful comments to the paper.

References

[1] Kerschner, R.L., 'Providing safe and practical environments for cultural property in historic buildings – and beyond', in Contribution to the Experts' Roundtable on Sustainable Climate Management Strategies, April 2007, Tenerife, Spain, ed. F. Boersma, The Getty Conservation Institute, Los Angeles (2007) http://www.getty.edu/conservation/our_projects/science/climate/climate_experts_roundtable.html#proceedings [accessed August 12, 2012].

[2] Michalski, S., 'The ideal climate, risk management, the ASHRAE chapter, proofed fluctuations, and toward a full risk analysis model', in Experts' Roundtable on Sustainable Climate Management Strategies, April 2007, Tenerife, Spain, ed. F. Boersma, The Getty Conservation Institute, Los Angeles (2007) http://www.getty.edu/conservation/education/panelpaintings/panelpaintings_component1.html [accessed August 12, 2012].

[3] European Standard EN 15757:2010 Conservation of Cultural Property. Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials (2010).

[4] Mohager, S., and Toratti, T., 'Long term bending creep of wood in cyclic relative humidity', Wood Science and Technology 27 (1993) 49–59.

[5] Hoffmeyer, P., and Davidson, R.W., 'Mechano-sorptive creep mechanism of wood in compression and bending', Wood Science and Technology 23 (1989) 215–227.

[6] Hutchings, J., 'The properties of alum. Investigations into the environmental sensitivity of alum-treated archaeological wood', in Proceedings of the 10th ICOM Group on Wet Organic Archaeological Materials, Amsterdam 2007, ed. K. Strætkvern, D.J. Huisman, Rijksdienst voor Archeologie, Cultuurlandschap en Monumenten, Amersfoot (2009) 589–614.

[7] Bonde, N., 'De norske vikingeskipsgraves alder. Et vellykket norsk-dansk forskningsprosjekt', Nationalmuseets Arbejdsmark (1994) 128–148.

[8] Rosenqvist, A.M., 'The stabilizing of wood found in the Viking ship of Oseberg – Part I', Studies in Conservation 4.1 (1959) 13–21.

[9] Montero, C., Gril, J., Legeas, G., Hunt, D.G., andClair, B., 'Influence of hygromechanical history on the longitudinal mechanosorptive creep of wood', Holzforschung 66.6 (2012) 757–764.

[10] Uzielli, L., Cocchi, L., Mazzanti, P., Togni, M., Jullien, D., and Dionisi-Vici, P., 'The Deformometric Kit: A method and an apparatus for monitoring the deformation of wooden panels', Journal of Cultural Heritage 13.3 (2012) 94–101.

[11] Hørte, T., Sund, O., Ronold, K., and Rove, H., Styrkeanalyse av Osebergskipet, Rapport nr. 2005–1615, revisjon nr. 02. Det Norske Veritas (2005) (unpublished).

[12] Brewer, A., and Forno, A., 'Moiré Fringe analysis of cradled panel paintings', Studies in Conservation 42 (1997) 211–230.

[13] Klein, P., and Bröker, F.W., 'Investigation into the deformations of panel paintings', in ICOM-CC Preprints 9th Triennial Meeting 26–31 August 1990, Dresden, German Democratic Republic 1990, ed. K. Grimstad, Getty Conservation Institute, Los Angeles (1990) Vol. I 41–43.

[14] Hailwood, A.J., and Horrobin, S., 'Absorption of water by polymers: analysis in terms of a simple model', Transactions of the Faraday Society, 42 (1946) B084–B092.

[15] Dionisi-Vici, P., De Vincenzi, M., and Uzielli, L., 'An analytical method for the characterization of the climatic distance of the microclimates for the conservation of wooden cultural heritage objects, Studies in Conservation 56.1 (2011) 41–57.

[16] Bratasz, Ł., Kozłowska, A., and Kozłowski R., 'Analysis of water adsorption by wood using the Guggenheim-Anderson-de Boer equation', European Journal of Wood and Wood Products 70.4 (2012) 445–451.

[17] Braovac, S., Fackler, K., Bader, T.K., and Ters, T., 'Chemical composition of the archaeological oak wood from the Oseberg ship', in Proceedings of the European Workshop on Cultural Heritage Preservation, Berlin, 26–28 September 2011, ed. M. Krüger, Fraunhofer IRB Verlag, Stuttgart (2011) 156–163.

[18] Mecklenburg, M.F., and Tumosa, C.S., 'Temperature and relative humidity effects on the mechanical and chemical stability of collections', ASHRAE Journal April (1999) 69–74.

[19] Knight, B., and Thickett, D., 'Determination of response rates of wooden objects to fluctuating relative humidity in historic properties', in Museum Microclimates. Contributions to the Copenhagen conference 19–23 November 2007, ed. T. Padfield, K. Borchersen, the National Museum of Denmark, Copenhagen (2007) 85–88.

Authors

Susan Braovac, **Guro Hjulstad**, **Maria Jensen** and **Elin Storbekk** are archaeological conservators at the Museum of Cultural History, University of Oslo and initiators of this research project. Email: susan.braovac@khm.uio.no

Ottaviano Allegretti is a researcher at IVALSA-CNR in San Michele all'Adige. He holds a doctorate in Wood Science and his field of research deals with wood-water relations in industry and related to cultural heritage. Email: allegretti@ivalsa.cnr.it

Paolo Dionisi-Vici is an associate research scientist at the Metropolitan Museum of Art, New York. He holds a doctorate in Wood Science and his activities at the Museum deal with the development of monitoring strategies for microclimates and for

measuring the response of objects to environmental fluctuations. He is the corresponding author. Email: paolo.dionisivici@ metmuseum.org

Image Credits

Figure 2. Poalo Dionisi-Vici
Figures 3 and 4. Susan Braovac

Licence

Comparison of indoor climate analysis according to current climate guidelines with the conservational investigation using the example of Linderhof Palace

Kristina Holl

Abstract

Linderhof Palace contains its original neo baroque furnishings, which consist of a large variety of composite materials. These artworks are affected by adverse indoor climate conditions such as cold temperatures and high relative humidity, which constantly fluctuates due to the high number of visitors. Depending on which guidelines are used, analysing and evaluating the indoor climate of a historic building can lead to different and sometimes opposing results concerning potential risks to the collection. The amplitude of fluctuations or the duration of a fluctuation affecting a certain kind of artwork are not considered in these guidelines. Some of the guidelines are based on the mechanical behaviour of objects, though only certain types of undamaged composite materials have been tested. Furthermore, it is unknown what risk of new damage is posed by deviating from the established environmental targets.

A detailed condition report on Linderhof's furnishings conducted 20 years ago was used to assess the present condition and to estimate the extent of changes induced by the climate over the last two decades. Different microclimates were identified, some of which had increased the rate of damage to the collection, such as flaking of gilded ornaments or painted wooden surfaces. The collection directly exposed to the external climate was particularly affected.

When these results were compared with an analysis of the indoor climate according to various recent guidelines it became apparent that many of the risks specific to each room at Linderhof were not covered by the usual statements of potential risk. Therefore, general climate guidelines are of limited use in estimating the potential for damage. In order to predict potential damage there is a pressing need to integrate knowledge about the characteristics of composite materials, their positions in the room and the possibility of the existence of distinct microclimates.

Linderhof Palace – more than a tourist attraction

Linderhof Palace, built by King Ludwig II is not only one of the most visited sites in Bavaria, it is also very interesting from a conservator's perspective. Most of the immovable furniture and fittings date to when Linderhof was built (1869–1885). The king's rooms on the upper floor are richly decorated with a large variety of materials (Figure 1), which respond in various ways to the indoor climate: painted ceilings, gilded stucco in the cavetto, oil paintings, gilded wooden ornaments on the walls and movable objects like tables and chairs, pastels, and textiles such as curtains, tapestries, and carpets, mainly produced by Bavarian artists. Little of the collection has been restored to date, with only a few repairs having been undertaken. Therefore all changes visible on the objects are related to the history and use of the building. The second point of

interest is that the indoor climate of the palace is strongly affected by the location of the building (Figure 1, 2) and by the high numbers of visitors, particularly in the summer.

Climate in the Linderhof Palace

The climate in the Linderhof Palace is extreme all year round. Situated near the Alps, the outdoor climate is affected by long periods of frost and snow in the winter, as well as by rapid weather changes in the summer. The temperature span is therefore very wide. In 2010, outdoor temperatures ranging from -17.3 °C to 30.5 °C were measured. The relative humidity (RH) is constantly very high, in 2010 the average was 90.8 % [3].

Linderhof Palace has no air-conditioning system, so the indoor climate follows the outside climate, buffered to some extent by the building. Therefore sub-zero temperatures in the state rooms occur regularly. In February 2012, -6 °C and 64 % RH were measured in the king's bedroom, the coldest room in the building.

Daily fluctuations of temperature and relative humidity are especially frequent in the summer months. Due to the high number of visitors, the windows are kept open to ensure adequate ventilation. During any 24-hour period, fluctuations of 30 % RH from the hourly mean may occur.[1]

The indoor climates of each room in the palace differ substantially. Two rooms located at opposite ends of the palace were chosen to illustrate the differences. The Hall of Mirrors is south facing, and the Lilac Cabinet is at the northwest of the palace. Climate data were captured from loggers located in the middle of each room. The graph (Figure 4) shows data from 11 January 2011 to 10 January 2012. The differences in temperature, relative and absolute humidity between both rooms are illustrated by the grey line. In the Lilac Cabinet, the relative humidity was always higher than in the Hall of Mirrors, while the temperature was always lower. The rooms have a mean difference in relative humidity of 9.7 %, and a mean temperature difference of 2 K, but both have similar daily fluctuations as figure 3 shows.

[1]This is dependent on the method of analysing data. See this volume pages 439–450

[2]In this context, short term is taken to be daily

Figure 1. Linderhof Palace in 1887, by Ludwig Sailer [1]

Figure 2. Historic furnishings in the Hall of Mirrors, by Franz Hanfstaengl c. 1890 [2]

Major risks for climate-induced damage to the Linderhof Palace collection

A literature review was conducted to evaluate the risks posed to the interiors and collection by the indoor environment. This identified the most hazardous characteristics as excessive relative humidity in general, frequent daily and seasonal fluctuations, and very low temperatures in the winter.

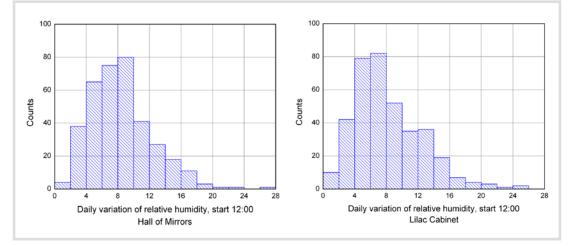### Relative humidity above 70 %

The sorption isotherms of many organic materials, for example, animal glue, demonstrate a minor sorptive response between 40 and 60 % RH, but a high change in dimension and mechanical properties above 70 % RH [5].
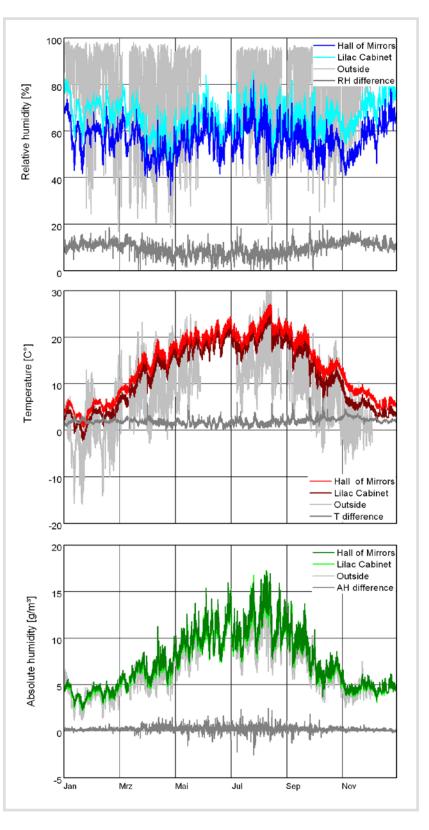
Furthermore, the higher the relative humidity, the more drastic the hydrolytic cleavage of cellulose [6]. This causes long-term degradation in composite materials like paintings or wooden objects. Above 70 % RH, the risk of mould growth on artworks consisting of organic compounds is evident [7]. However, there are factors other than temperature and relative humidity which increase the risk of mould growth, such as substrate quality and the duration of coincidence. The American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) recommends maintaining an RH of below 75 % as the most basic level of environmental control, class D [8].

Fluctuation of relative humidity

Artworks consisting of organic materials swell and shrink with changes in relative humidity. Depending on the length and amplitude of the fluctuations, it is likely that there will be deterioration over time. The definition of an acceptable climate varies according to the author and the classification of the building in question. The ASHRAE standards dictate that fluctuations above 2.5 % per hour and 5 % per day are too high for a museum to be classified as AA standard [8, 9]. For historic buildings like the Linderhof Palace, Erhardt et al. assume, that short-term fluctuations[2] of 10 to 15 % above or below the monthly or annual average are still acceptable [6]. European Standard CEN/ TC 346 recommends that the target range of indoor climate (when conditioned) should be within the 7th and 93rd percentile

Figure 3. Histogram of the daily variation of relative humidity by the hourly mean. Left: Hall of Mirrors; Right: Lilac Cabinet. Both rooms show similar daily fluctuations of RH

Figure 4. Line diagram of temperature, relative humidity and absolute humidity in the Hall of Mirrors and the Lilac Cabinet compared to the outside climate. Differences between both rooms are displayed in the dark grey line in each diagram
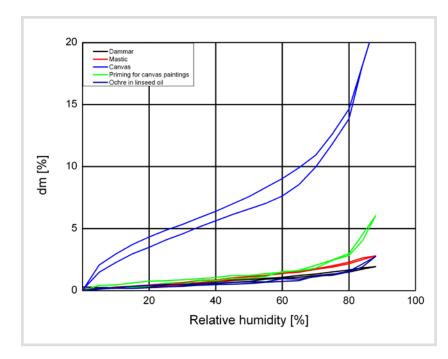
of measured values so that the driest and most humid extremes are avoided [10]. These guidelines mainly derive from theoretical approaches or from laboratory tests with un-aged materials combined with simulations.

Cold temperatures

Paintings, particularly in oil and acrylic, can be strongly affected by temperatures below zero due to their low glass transition

temperatures. They can become brittle and flake. In this case, the effect of temperature is far more detrimental than the effect of relative humidity [11].

Evaluation of the indoor climate in the Linderhof Palace using different guidelines

In the following table, the three major risks related to the indoor climate in the Linderhof Palace are analysed according to various guidelines taken from the literature. Data from the Hall of Mirrors and the Lilac Cabinet reflecting the indoor climate for a period of one year were used. As the guidelines referring to average indoor climates do not usually take into account local microclimates, data from the surface measurement in the Lilac Cabinet were used for comparison. The percentage of data exceeding the limits recommended in the literature are listed below.

The table shows that climate data values for the Hall of Mirrors are in line with Thomson's recommended range as well as that of ASHRAE's control class D. Taking Thomson's guidelines for the Lilac Cabinet, however, the recommended range was exceeded by 27.8 % of the data recorded in the middle of the room and by 33.5 % on the surface. This is due to the higher relative humidity in the Lilac Cabinet. ASHRAE's control class D range was exceeded by 8.6 % of the data measured in the room and by 16.9 % of the data collected from the surface.

The data from all three locations fell beyond the recommended range established by deviation from the annual mean RH by plus or minus 10 to 15 %. Each location fell beyond the range by a similar amount. Assuming a 'moderate RH region' is around 50 to 55 %, the data falling beyond the plus/minus 10 to 15 % of this range increase for both measurement sites in the Lilac Cabinet: 50 % of the data on both measurement sites exceeded 55 plus or minus 10 % RH; 23 % in the middle of the room and 30 % on the surface position exceeded 55 plus or minus 15 % RH. The comparison of climate guidelines does not lead to a clear result. Interpreting the guidelines for relative humidity would imply that the historic

interiors in the Hall of Mirrors should be in a better condition than in the Lilac Cabinet. Taking into account the data from the surface measurement it seems likely that more damage can be found on the collection situated near the outer walls. In terms of the low temperatures in the Palace, it is also likely that damage will be identified on artworks which have a low glass transition temperature as there are low temperatures in all rooms.

The impact of daily and seasonal fluctuations in temperature and relative humidity is not considered in sufficient depth by the guidelines, nor is there enough attention devoted to the varying responses of different classes of materials. Depending on their physical properties, materials react to environmental changes very differently. Structurally dense, composite objects such as gilded or coated wood are much less responsive to climatic changes than more permeable materials, as the movement of moisture through the structure takes so much longer. The thickness of the various layers of material is also a major factor.

It is vital to distinguish the particular material or composite materials to which these guidelines refer. For example, painted or gilded wooden objects are damaged severely by seasonal environmental fluctuations, which can cause cracking in the wood [13], while very sensitive materials like parchment react immediately and visibly to very short fluctuations of relative humidity.

In summary, it is necessary to verify the estimates of risk implied by the data by investigating the actual condition of objects and interiors:

• What is the condition of various objects of different composite materials installed in the palace?

Table 1. Indoor climate data from the Hall of Mirrors (air) and the Lilac Cabinet (air and surface) analysed by different guidelines taken from literature

Literature	Description	Hall of Mirrors – sensor in the middle of the room	Lilac Cabinet – sensor in the middle of the room	Lilac Cabinet – sensor on the outside wall
		Data exceeding the limit	Data exceeding the limit	Data exceeding the limit
Thomson [12]	40 to 70 % RH	1.8 %	27.8 %	33.5 %
ASHRAE, class of control D [8]	Data should stay below 75 % RH	0.1 %	8.6 %	16.9 %
Erhardt et al. [6] ASHRAE class of control B [8]	"Changes caused by environmental fluctuations ± 10–15 in the moderate RH region are generally reversible"	Annual mean 56 % ± 10 % = 46–66 % RH: 12.6 %	Annual mean 66 % ± 10 % = 56–76 % RH: 6.9 %	Annual mean 67 % ± 10 % = 57–77 % RH: 11.5 %
Erhardt et al. [6]	"Changes caused by environmental fluctuations ± 10–15 in the moderate RH region are generally reversible"	Annual mean 56 % ± 15 % = 41–71 % RH: 1.2 %	Annual mean 66 % ± 15% = 51–81 % RH: 2 %	Annual mean 67 % ± 15 % = 52–82 % RH: 1.4 %
Mecklenburg [11]	Temperature below 0 resp. 8 °C	< 0 °C: 0 % < 8 °C: 26.5 %	< 0 °C: 1.4 % < 8 °C: 35.5 %	< 0 °C: 2.4 % < 8 °C: 15.8 %

- Does the condition of furnishing and objects vary in different rooms?
- Does the location of the furnishing or object in the room influence condition?

Method of investigation of the state of preservation

Condition photographs were compared in order to evaluate deterioration and damage during recent years. A photographic condition survey of all immovable furnishings was undertaken in 1992. Certain types of damage were identified in this survey. For example, flaking and cracks in gilded surfaces, which indicate climate-related deterioration, as well as water marks caused by historic water leaks or surfaces which had been abraded due to touching by visitors. This type of damage was described and photographs of particular examples were taken in every room. These images allowed the condition of the collection in the 1990s to be compared with the present condition. Oil paintings and gilded surfaces were selected for particular investigation as these were best documented. Due to the risk of mould growth at high relative humidities, particular care was taken to examine corners with little air exchange or air flow.

The gilded ornaments were composed of wooden supports, glue layers, priming, bolus, covered with gold leaf and a coating. Only the gilded wooden decoration on the walls in the bedroom was created with a different technique, here the wooden support had very thin priming and the gold leaf was fixed with an oily binding media.[3] The oil paintings had a thin priming, with a thin occasionally opaque paint layer, covered with a varnish.

Results of the in situ investigation

Different observations can be made about the various materials examined. Fragile objects, for example pastels and textiles, were greatly affected by the climate. Materials insensitive to environmental changes, such as porcelain vases, were in a very good state of preservation. Furnishings located in the middle of the room had not changed significantly during the last two decades. Damage like loss of gilded surfaces were already visible on the pictures from 1992 (Figure 6).

The greater fluctuation in relative humidity caused by the use of the historic heating system when the king was attendant might be one of the causes of the pre-existing damage.[4]

The cardinal direction of the room did not appear to influence condition. However, the surface condition of wooden gilded objects on the walls in the bedroom varied according to production technique.

The biggest changes in condition were observed in gilded wooden decorations installed near to or on outer walls (Figure 7). Most notably the folding shutters, decorated with gilded sand-textured surfaces and wood carved ornaments, presented heavy losses and loosening. Paintings on canvas hanging on outer walls, as in the audience chamber, were heavily warped as a result of their exposure to severe environmental fluctuations. Only few craquelures were visible.

[3] The bedroom has been adapted by Ludwig II and was not finished before his death. This was realized only after the palace was opened to the public

[4] Historic documents describe early repairs to the historic furnishing, for example cracked pieces of lapis lazuli on the fireside in the Hall of Mirrors

Mould growth[5] was found in many areas, particularly in corners where the air exchange was very low, such as in folded shutters and the state bed (Figure 8). Separated from the visitors by a balustrade, the wooden gilded bed, furnished with a coating made of glue, presents an ideal medium for fungi. In some areas the painted wooden surfaces, which have been painted over with an acrylic medium, are flaking probably due to temperatures below the glass transition temperature of the binder.

Combining the results from the in situ investigation with the estimates from the climate data analysed, it is possible to conclude that, in general, the prediction of little damage for the historic furnishing situated in the middle of the room was broadly correct. More in depth predictions, specific to particular composite materials, could not be made. It was not possible to confirm differences in the condition of the same types of furnishings located in different rooms. Surprisingly, the condition of the gilded surfaces on the walls in the bedroom, the room with the highest RH and the coldest temperatures, was very good. This confirms that the particular gilding technique, which was different from the other rooms, is a major influence in the preservation.

Conclusion and outlook

This comparison of predictions drawn from an analysis of environmental data with a conservation condition survey has demonstrated that the predictions derived from the climate data alone are limited. The results of the environmental data analysis differ according to the particular guidelines used, which undermines the efficacy of such an approach. A room never has one single climate, and there is most potential for damage in extreme local microclimates. When predicting future damage, it

Figure 6. Audience room, east wall, gilded ornaments on the baldachin: losses and loosening of the gilded surfaces have not increased during the last 20 years

Figure 7. Yellow Cabinet, western wall, heavy losses to the silvered ornaments

Figure 8. Mould growth on the gilded state bed in the King's bedroom

is also necessary to take into account the specific characteristics of different composite materials. Last but not least, there is a considerable lack of knowledge about the risk of new damage posed by long-term deviation from the environmental guidelines. Fluctuations are not the only risk historic furnishings are exposed to. Light and pollutants have a major influence. In historic interiors it is not always easy to distinguish between single influences, and it is likely that there will be some deterioration factors which are interlinked and mutually dependent.

Linderhof was an attempt to compare guidelines derived from analysed climate data with results from a conservation condition survey. More buildings should be investigated to produce more reliable predictions and results. In order to better understand the risks posed by environmental fluctuations to collections in real conditions, further investigations are necessary into material characteristics, for example, simulations of hygrothermal processes on different artworks and in situ measurements with infrared thermography or 3D digitizing investigations.

Acknowledgements

References

[1] Sailer, L., The Art Monuments of his Late Majesty King Ludwig II. of Bavaria. A guide and souvenir for visitors to the royal palaces of Herrenchiemsee, Neuschwanstein, Linderhof, Hohenschwangau, Berg and the hunting seat at the Schachen by Ludwig Sailer, Munich (1887).

[2] Hanfstaengl, F., Pigment-Druck der königl. Schlösser zu Chiemsee Linderhof, Franz Hanfstaengl Kunstverlag, München (ca. 1890).

[3] Bichlmair, S., Simulation und Analyse des Raumklimas in ausgewählten Räumen im Schloss Linderhof, Masters thesis, Hochschule Rosenheim (2011) (unpublished).

[4] Bichlmair, S., Holl, K., and Kilian, R., 'The moving fluctuation range – a new analytical method for evaluation of climate fluctuations in historic buildings', see this volume pages 439–450.

[5] Stolow, N., Conservation and Exhibitions. Packing, transport, storage, and environmental considerations, Butterworths, London (1987).

[6] Erhardt, D., Mecklenburg, M., Tumosa, C., and McCormick-Goodhart, M., 'The determination of appropriate museum environments', The Interface Between Science and Conservation: British Museum Occasional Paper 116, ed. S. Bradley, British Museum, London (1997) 153–163.

[7] Sedlbauer, K., Vorhersage von Schimmelpilzbildung auf und in Bauteilen, Dissertation Universität Stuttgart (2001).

[8] American Society of Heating, Refrigerating and Air-conditioning Engineers, 'Museums, libraries and archives', in ASHRAE Handbook: Heating, ventilating, and air-conditioning applications, SI edition, AHSRAE, Atlanta, Georgia (2007) 21.1–21.23.

[9] Burmester, A., 'Die Beteiligung des Nutzers bei Museumsneubau und -sanierung oder welche Klimawerte sind die richtigen?', in Raumklima in Museen und historischen Gebäuden, ed. Fachinstitut Gebäude-Klima e. V., Bietigheim-Bissingen (2000) 9–24.

[10] European Standard CEN/TC 346 EN 15757, Conservation of Cultural Property – Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials, European Committee for Standardization, Brussels (2010).

[11] Mecklenburg, M., 'Determining the acceptable ranges of relative humidity and temperature in museums and galleries, Part 2, structural response to temperature', http://www.si.edu/mci/downloads/reports/Mecklenburg-Part2-Temp.pdf

[12] Thomson, G., The Museum Environment, 2nd edn, Butterworths, London (1986).

[13] Rachwał, B., Bratasz, Ł., Łukomski, M., and Kozłowski, R., 'Response of wood supports in panel paintings subjected to changing climate conditions', Strain 48.5 (2012) 366–374.

Author

Kristina Holl is a scientific officer at the Fraunhofer Institute for Building Physics, Holzkirchen. She is also writing her PhD thesis on climatic fluctuations on works of art, funded by the Scholarship Programme of the German Federal Environmental Foundation. Email: kristina.holl@ibp.fraunhofer.de

Image credits

Figure 6 left: 1992 Kriewitz/Mayrhofer, right: 2012 Holl/Raffler
Figure 7 left: 1992 Kriewitz/Mayrhofer, right: 2012 Holl/Raffler
Figure 8. 2012 Holl/Raffler

Licence

Quantification, the link to relate climate-induced damage to indoor environments in historic buildings

Charlotta Bylund Melin and Mattias Legnér

Abstract

This paper describes and applies a method to quantify and relate damage of painted wooden pulpits in 16 churches in Gotland, Sweden, to both the current and the historical indoor climate of the twentieth century. In addition, it demonstrates that the energy used to heat a church in the past can be measured and the study also points towards a relationship between damage and heat output. The results suggest that more damage is present in churches with a higher heat output and there is increased damage in churches using background heating compared to churches that do not. However, the method needs to be improved and a larger population is required to validate these results.

Introduction

One of the most challenging tasks today in the cultural heritage sector is to determine the influence of present and future climates on historic buildings, interiors and collections. Some of the objectives of the ongoing European Seventh Framework Program Climate for Culture (CfC), Work Package (WP) 4, Damage Assessment are to increase knowledge about the cause-effect relationship between indoor environment, relative humidity (RH) and temperature (T) and the state of preservation of collections. This includes determination of tolerable RH and T ranges for different materials as well as the correlation between the historic climate and state of preservation [1]. Laboratory studies [2], mock up studies in museums [3] as well as studies of single objects in historic buildings and modelling [4] have been performed. However, to further validate these results complementary surveys of larger numbers of object types in their actual historic microclimates are also needed. This is emphasised in the subproject, CfC WP 4.1, Statistical assessment of actual damages in relation to indoor climate in a representative population of historic buildings. Such surveys will add relevant information to the research area of climate-induced damage, but the subject is also very complex, which is probably one reason why they have been performed only in limited numbers.

There are many possible uncertainties in the cause-effect relationship between the deterioration of organic materials and their indoor environments and so it is difficult to draw reliable, comparative conclusions. The cause, both the set point and short-term fluctuations of RH and T will have varied over time and cannot be isolated from other influencing factors such as light and air pollution. Even if RH and T records are available from the churches over certain periods, there is no useful way of quantifying the indoor climate, either in the present time or from a historic perspective. The effect on objects of organic materials, their constituents, age, manufacturing techniques and history is the sum of the visible, permanent damage and change; hence the

state of preservation of the objects as seen today is the sum of all those cumulative factors from the past. Due to the lack of methods to quantify the historic and present indoor climate as well as the damage and change of objects, it is not possible to relate these two parameters to each other.

The Island of Gotland is located in the Baltic Sea, about 90 km from the Swedish coast. Its central position in the Baltic has made it an important harbour, which has promoted trading and resulted in long periods of great wealth. From the twelfth century until c. 1350, 92 churches were erected on the island, constituting a cultural heritage of great value. Both the exteriors (Figure 1) as well as the interiors (Figure 2) of these churches have many similarities. The churches are all located within an area of less than 3184 m² and are exposed to the same oceanic climate. They are all made of local sandstone or limestone and all interior walls are rendered and the ceilings and floors are stone or partly of wood. In the late sixteenth century, pulpits and other furnishing associated with Lutheran liturgy were introduced to the churches. Due to their high cultural heritage value, major works undertaken in the churches, such as restoration and renovation of interiors or the introduction of new heating systems, have been systematically recorded since the 1920s. When the objects in these churches are examined it is possible to observe damage which can be related to the indoor environment, although the extent varies between churches. This is particularly noticeable on painted wooden objects. One reason for this may be the differences in indoor climates between churches, but until now the heat output (energy used for space heating) over a long period of time has not been connected to the climate-related damage observed in churches.

The aim of this pilot study is to propose an interdisciplinary approach to investigate whether a set of pre-selected damage patterns which are known to be caused by fluctuating and high RH and T (indoor climate indicators), in combination with

Figure 1. Levide church, a typical Gotland church

documentation on historic heating can be used as proxies [5] for the historic indoor climate.

The hypothesis is that by studying and comparing a large number of similar, immovable objects in indoor environments which do not accord with recommendations on museum climates [6] it should be possible to distinguish patterns of damage caused by different climate conditions. Although the approach will give an approximation only, the damage will be able to provide indications of past and present indoor environments.

From a research perspective, the Gotland churches are a good model base for population studies. The method used for this survey was to assess damage in 16 of the 92 churches. These particular churches were selected to represent the different heating regimes used in Gotland churches. Heating of the nave was first introduced in rural Gotland churches around 1900. The oldest kind of heat source was the Gurney´s oven (Figure 3).

When central heating (CH) was introduced it was usually in the form of low-pressure steam that gave off an intense heat and was difficult to control. In the 1940s to 1950s, older CH systems were, with a few exceptions, replaced by either low-pressure hot water or electrical space heaters.

The objects chosen for the survey were pulpits (Figure 5). They are commonly found in the churches and on Gotland they are made of local wood (normally pine). They were originally painted polychrome using oil paint [7]. In the majority of the churches they are located in their original positions e.g., the south-east corner of the nave, and have only on rare occasions been moved. The pulpits are fully or partly freestanding, avoiding microclimate conditions which can develop around objects in close contact with an exterior wall.

Method

By studying a population of similar objects which have not been moved from their original environments it may become possible to relate specific damage patterns to certain indoor climates. In this context it becomes more important to study a large number of objects rather than looking at individual objects and buildings. This section will briefly describe the methods for 1) quantification of energy used for heating and 2) the survey of indoor climate indicators for wood and painted layers.
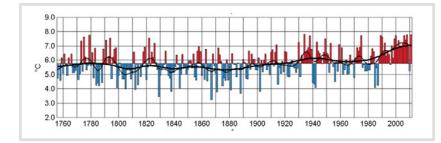
Heating

Until now, the past heating of historic buildings has rarely been studied [5, 8]. Evidence-based knowledge is largely lacking, despite the prospect of researching past energy use in churches being relatively good in Sweden [9, 10]. In general, data on past indoor T and RH in churches are not available, which is also the case for the 16 churches studied. In order to document how the indoor climate may have fluctuated in a church, archival sources are used, which provide indications of what the climate was like. Documentation on heating systems and historic fuel consumption is available for almost all of the churches. The information on heating systems is held by Antikvariskt-Topografiskt Arkiv (ATA) and can also be found in management plans kept at Gotland's museum. In some cases when management plans proved incomplete, it was possible to use parish records to fill in the gaps. Parish accounts, which contain data on fuel consumption, are available through Visby Arkivcentrum.

The first step in this research was to identify the different kinds of heating used in the churches and map when alterations were made. The next step was to extract data on how much fuel (and energy) each system used. The accounts of each parish were consulted for this purpose. For each five-year interval, one year

Figure 3. Fröjel church. Opposite the pulpit is a Gurney type of oven located in the north-east corner of the nave. Source: ATA, The National Heritage Board (photographer: H. Faith-Ell, 1931)

was examined: 1900, 1905, 1910, etc. Fuel consumption in the
parish accounts was then converted to efficiency, measured in
watts/hour (kW/h). Each kind of fuel has a specific energy content
given by the Swedish Environmental Protection Agency.

Having established information on annual energy consumption, the
amount of energy utilised (efficiency) then had to be estimated in
order to quantify the output. Some of the energy consumed is lost
in the process and does not add to heat introduced to the building
[11]. In the end, these calculations give a total estimate of how
much energy was added to the heating of the church between the
years 1900 and 1990 (Table 1). These values were then divided
by the area of the church in order to compensate for the volume
heated. As data on the volume of spaces was missing, floor areas
were used instead. A large floor area indicates a voluminous
church. Finally, the total heat output was multiplied by five since
only every fifth year was examined. In the last column in table 1,
the total heat output values are divided into three groups, low,
medium and high so they can be compared. The estimates for
background heating (Table 1) should be viewed as approximate
figures as the temperature has most certainly varied significantly
in reality.

Today, all churches are heated intermittently but there was no
RH control in any of them before the 1990s. Data on background
heating, used in 11 of the 16 churches, was obtained from the
parishes. The other five churches are allowed to cool down
between the sermons. A sudden rise in heat output (Figure 6)
indicates a drastic change of the heating regime, for example the
introduction of background heating, or it could relate to one or
several extremely cold winters. As seen in figure 4, the winters of
the 1910s and 1920s were unusually cold, and the winters during
World War II (when churches were rarely heated) were very cold.
There were also a few very cold winters in the mid-1980s. On the
other hand, a considerable drop in energy output would indicate a
shift in heating regime or one or more mild winters.

Damage and selection of indoor climate indicators

Damage assessments as well as risk assessments are used in
the field of conservation to quantify the condition of collections.
Both the terms 'risk' and 'damage' are related to a change in
value and usefulness. However, these factors may influence the
overall assessment and hence the outcome of the survey [12, 13].
Methods of using more focused indicators have been used for
specific purposes by Bucklow [14], Brunskog [15, 16] and Bylund
Melin et al. [17]. In the present damage assessment, the pulpits
are regarded strictly as a population, subjected to climate-induced
damage and the indicators are simply recorded and quantified
without further interpretation. Observed examples of damage

Figure 5. The pulpit
in Hörsne church

visible to the naked eye or by using a handheld microscope were
utilised in the survey and the following indoor climate indicators
for wood and paint were selected by the experience gained from an
earlier pre-study.

The pulpits consist of interlinking wooden elements, which can
become visibly deformed as the elements can act as restraints on
each other. Visible signs of mechanical deformation are cracks,
open joints and shrinkage, as revealed by unpainted edges where
the wooden elements overlap.

Flight holes from wood-boring beetles are common in wooden
objects in the Gotland churches, although it is not always possible
to judge infestations are ongoing or historic [18]. From the archive
records, it is obvious that infestation has been a problem in the
Gotland churches for decades or even longer and measures were
regularly taken to remove them.

Mould hyphae are visible on some pulpits and were recorded
although strictly speaking the mould is causing the damage, it is
not the damage itself. The visible hyphae can be, and have been,
removed and so cannot be regarded as permanent damage.

Originally the pulpits were painted with polychrome oil paint [7]. The extent to which hide glue, gesso grounds or varnish were used is uncertain. Today, remains of a white ground are visible in some areas, while other parts of the same pulpit exhibit no traces. The pulpits have also been repainted and restored on one or several occasions, which is also supported by archive records. Active delamination of the paint layers is only rarely seen.
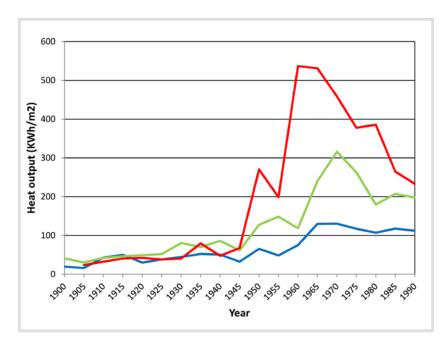
In contrast, a network of fine cracks (craquelures) perpendicular to the paint surface is often visible in the painted surface. Drying cracks (developed during the drying of the paint) would show random craquelure patterns while aging cracks (developed in the older and more brittle paint layers) present craquelure patterns more parallel to the grain of the supporting wood [19]. Both these types of craquelures are present on the pulpits. As aging cracks can be related to the moisture movement of the wood, the two types were recorded separately. Mecklenburg [19] and Bucklow [20] have pointed out that oil paints containing different pigments have different RH-related mechanical and dimensional properties. It was clear that this phenomenon was present as adjacent areas of surface painted with different colours could show different craquelure patterns or amounts of craquelures. Therefore the damage assessment was also performed using the craquelure patterns for the most common colours in the pulpits, e.g. white/light grey, brown, black, red, skin colour (carnation), blue and green. Each colour was not present on all pulpits and the size of each coloured area varied among the pulpits.

It was important to quantify the damage so comparisons could be undetaken. Methods like detailed photographing of the painted

Table 1. Present background heating and total heat output in the 16 Gotland churches. The estimated total heat output values (MWh/m^2) are multiplied by five to compensate for the years that were not examined

Church	Background heating T, (°C)	Heat output (MWh) 1900–1990	Floor area of church (m²)	Estimated total heat output (MWh/m²) 1900–1990	Low heat output < 8 Medium 8–15 High >15 (MWh/m²)
Akebäck	8	168	127	6,6	Low
Alskog	6	430	224	9,6	Medium
Björke	9	672	162	20,7	High
Bunge	None	773	319	12,1	Medium
Buttle	10	324	146	11,1	Medium
Dalhem	8	746	370	10,1	Medium
Etelhem	5	525	255	10,3	Medium
Fide	None	143	153	4,7	Low
Fröjel	12	453	208	10,8	Medium
Hejde	7	458	205	11,2	Medium
Hörsne	6	459	175	13,1	Medium
Levide	None	211	179	5,9	Low
Roma	9	1738	430	20,2	High
Vänge	9	501	219	11,4	Medium
Öja	None	509	369	6,9	Low
Östergarn	None	234	280	4,2	Low

surfaces, computer monitoring and calculating of damaged surfaces in relation to undamaged etc. were discussed but were considered unhelpful because some areas were too small to register or did not have distinct borders. From the experience of the earlier pre-study of the pulpits it seemed possible for the examiner to make a subjective quantification. The quantifications were made as blind tests as the specific heating systems of the churches were not known during the assessment. Only the naked eye, an LED-torch and a handheld microscope were used for the inspections. It was decided to use four grades on a relative scale to quantify the damage:

0 points = no damage
1 point = small number of damaged areas
2 points = medium number of damaged areas
3 points = large number of damaged areas

Each damage pattern was inspected on all sides of the pulpits before registering the score and an average of 20 to 30 areas were observed before deciding the final score. In some instances the incoming daylight from the south-facing windows had caused increased deterioration of the paint on one side of the pulpits so those sides were excluded from the survey:

Results

It has been shown that the degree of heating in churches has varied over time, and that these variations can be tracked by using archival sources. This means that it is not necessary to speculate how a particular church was heated in the past. Figure 6 shows the fluctuation in heat output for each five-year interval in the 16 churches. The general tendency is that there was a low and stable heat output during the first half of the century. After World War II there was a strong increase in heat output. It is also noticeable that the larger the total heat output, the larger the fluctuations. Table 1 shows that there is a relationship between present background heating and total heat output, e.g., churches without background heating generally show low heat output.

The damage as an individual parameter or in combination was related to indoor climate variables as seen in table 2. It is known that permanent heating in historic buildings has caused incalculable damage to painted wooded objects [21] if the relative humidity is not controlled.

When the different background heating temperatures were compared (5 to 12 °C) with the condition of the pulpits it had been assumed that higher temperatures would cause more damage. No relationship was identified, however. By dividing the churches into two simple groups, those with and without background heating, a clearer pattern emerged; more damage craquelures were observed in churches with background heating (Figure 7).

This tendency was clear for all colours, except green, on all pulpits. Making the same type of comparison between the different colours and the total heat output did not show the same relationship. However, a comparison of the three levels of total heat output with the total damage scores for all craquelures of all colours for each pulpit showed lower damage scores in churches with lower heat output when compared with those with medium heat output (Figure 8). The same relationship is also found in churches with and without background heating. There is also an increased frequency of paint delamination in churches with background heating.

No such relationship was identified for mechanical deformation of the wood. For mould, an increase was found in churches with background heating whereas flight holes were more frequent in churches without background heating.

Discussion

There is a large number of variables among the churches such as volume, heating systems, presence of moisture-buffering materials and different air leakages due to the building envelope.

Table 2. The relation between the indoor climate and damage

Type of damage (indoor climate indicator)	The relationship between churches with and without background heating and damage	Relation between the total heat output (MWh/m²) 1900–1990 and damage
Mould	Mould is more frequent in churches with background heating	None
Flight holes	Flight holes are more frequent in churches without background heating	None
Mould + flight holes	None	None
Cracks in wood	None	None
Open joints	None	None
Cracks + open joints	None	None
Paint delamination	Paint delamination is more frequent in churches with background heating	None
Craquelures (aging)	Slight correlation. Less damage in churches without background heating	None
Craquelures (drying)	None	None
Craquelures (aging + drying)	Yes, less amount craquelures in churches without background heating (Figure 7)	Yes, less craquelures in churches with the least heat output (Figure 8)

Figure 7. The relation between damage score of the different colours on the pulpits in the 16 churches with and without background heating. For all colours, except green, there are more craquelures (higher damage score) in churches with background heating (red bars) compared to churches without (blue bars). For red and carnation colours there are no craquelures in churches without background heating and hence no blue bars in the diagram
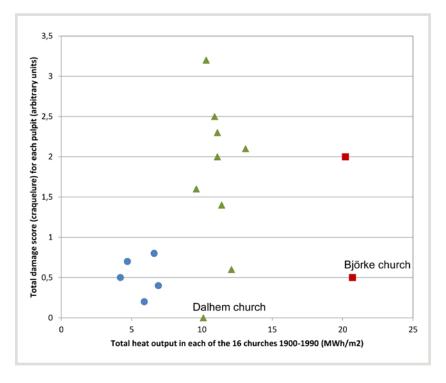
Figure 8. The relation between the total heat output (MWh/m^2) and total damage score for craquelures of all colours of each pulpit in each church. The group of red squares are the damage scores from pulpits in churches with high heat output as presented in table 1 (> 15 MWh/m^2). Green triangles are pulpits representing medium heat output (8 to 15MWh/m^2) and blue circles are low heat output (< 8 MWh/m^2). The two outliers, Dalhem and Björke churches showing low damage scores have pulpits which were repainted by the same painter, C. W. Pettersson, as late as the beginning of the twentieth century and therefore craquelures may not yet have developed

Furthermore, the variety of the pulpits in terms of age, method and number of restorations and the lack of knowledge about the exact constituents of the paint layers and so on could be used to argue that a survey like the one presented in this paper is not valid. Despite this, slight relationships have been identified which suggest that the approach of relating past indoor climate to indoor climate indicators is a method that could be further developed.

Many questions have arisen during the survey; are all damage patterns studied here useful, should some be excluded or others included? The survey indicates that the craquelure patterns are the most useful of damage patterns explored as they present a large degree and range of quantifiable damage. It can be dangerous to make such assumptions as it also indicates that the damage in wood might prove useful if a larger population was incorporated. Is it possible to neglect other agents of deterioration like light and air pollution from a survey like this? The light levels in the buildings should also be taken into account, as well as variations in outdoor climate conditions.

There seems to be a relationship between low damage scores and churches without background heating and with low total heat output. This supports the assumption that saving energy in the churches by not using background heating also benefits the preservation of the paint layers on the pulpits.

Perhaps the most important intention of this survey was to find an affordable and efficient method to make assessments of past indoor climate and damage inflicted that can be compared between a large number of locations. Therefore the weakest part in this survey is the damage assessment. To find a method for quantification of damage that is both objective and reproducible, Bucklow [14] suggests having a set of reference standards which can be used even by inexperienced conservators or art-historians to assess craquelure patterns. Something similar may be applicable though it would need to be developed by experienced conservators. It would also be valuable to make similar assessments of other groups of materials.

Our study shows that there are many difficulties to overcome and that the method presented here should be further developed and improved. However, measuring both the cause and the effect allows them to be quantified and compared. Further studies relating actual monitored relative humidity and temperatures to known energy consumption and heat output in different churches would demonstrate if the archive records proxies were reliable. In this respect, simulations of the indoor environment could prove useful. For both the proxies as well as the indoor climate indicators a larger population would validate the methods as well as the results.

References

[1] Climate for Culture website, http://www.climateforculture.eu/ (accessed 30 August 2012).

[2] Mecklenburg, M.F., Tumosa, C.S., and Erhardt, D., 'The changing properties of aging oil paints', Material Research Society Symposium Proceedings 852 (2005) 12–24.

[3] van den Brink, O.F., Eijkel, G.B., and Boon, J.J., 'Dosimetry of paintings: determination of the degree of chemical change in museum-exposed test paintings by mass spectroscopy', Termochimica Acta 365 (2000) 1–23.

[4] Bratasz, L., Jakiela, S., and Kozłowski, R., 'Allowable thresholds in dynamic changes of microclimate for wooden cultural objects: monitoring in situ and modelling', in ICOM Committee for Conservation, 14th Triennial Meeting, Preprints, ed I. Verger, James & James, London (2005) Vol. II 582–589.

[5] Cassar, M., and Taylor, J., 'A cross-disciplinary approach to the use of archives as evidence of past indoor environments in historic buildings', Journal of the Society of Archivists 25.2 (2004) 157–172.

[6] Thomson, G., The Museum Environment, 2nd edn, Butterworth, London (1986).

[7] Eliasson, C-H., private painting restorer, Gotland, personal communication, September 2011.

[8] Legnér, M., 'On the early history of museum environment control: Nationalmuseum and Gripsholm Castle in Sweden, c. 1866–1932', Studies in Conservation 56 (2011) 125–137.

[9] Legnér, M., 'Tracing the historical indoor climate of a Swedish church, c. 1800–2000', APT Bulletin XLIII (2012) 49–56.

[10] Legnér, M., and Geijer, M., 'Heating regimes in old Swedish churches, c. 1880–1980', in Paper for the 2nd European Workshop on Cultural Heritage Preservation, Oslo 24–25 September 2012 [In print].

[11] Rietschel, H., and Raiss, W., Lehrbuch der Heiz- und Lüftungstechnik, Springer Verlag, Berlin (1960).

[12] Ashley-Smith, J., Risk Assessment for Object Conservation, Butterworth Heinemann, Oxford (1999).

[13] Taylor, J., and Stevenson, S., 'Investigating subjectivity within collection condition surveys', Museum Management and Curatorship 18.1 (2000) 19–42.

[14] Bucklow, S., 'A stylometric analysis of craquelure', Computers and the Humanities 31 (1998) 503–521.

[15] Brunskog, M., 'Japanning in Sweden 1680s–1790s. Characteristics and preservation of orientilized coatings on wooden substrates', Göteborg Studies in Conservation 11, Acta Universitatis Gothoburgensis, Göteborg (2004) [Dissertation].

[16] Brunskog, M., 'Paint failure as potential indicator of cool indoor temperature', in Postprints from the Conference Energy Efficiency in Historic Buildings, Visby, February 9–11, 2011, ed. T. Broström, L. Nilsen, Gotland University Press, Gotland (2012) 30–36.

[17] Bylund Melin, C., Bjurman, J., Brunskog, M., and von Hofsten, A., 'Painted wood as a climate indicator? Experiences from a condition survey of painted wooden panels and environmental monitoring in Läckö Castle, a dehumidified historic building', in Multidisciplinary Conservation. A holistic view for historic interiors, Rome 23–26 March 2010. ICOM-CC Interim meeting, ed. M. Sawicki, ICCROM, Rome, http://www.icom-cc.org/54/document/painted-wood-as-a-climate-indicator--experiences-from-a-condition-survey-of-painted-wooden-panels-and-environmental-monitoring-in-lck-castle-a-dehumidified-historic-building/?id=817 (accessed 14 August 2012).

[18] Nolt, U., Johann Heinrich von Thünen Institute, Hamburg, personal communication, 12–13 May 2012.

[19] Mecklenburg, M. F., 'Determining the acceptable ranges of relative humidity and temperature in museums and galleries. Part 1 structural response to relative humidity', http://www.si.edu/mci/downloads/reports/Mecklenburg-Part1-RH.pdf (accessed 31 August 2012).

[20] Bucklow S., 'Pigment-medium interaction: visible evidence', in Deterioration of Artists´ Paints: Effects and analysis. A joint meeting of ICOM-CC Working Group Paintings 1 & 2 and Paintings Section, UKIC. Extended abstracts of presentations. British Museum, London (2001) 49–52.

[21] Tångeberg, P., 'Skador på måleri I svenska kyrkor. En lägesrapport. Restaureringsprinciper', Fornvännen 74 (1979) 113–125 [In Swedish].

Authors

Charlotta Bylund is a conservator and currently a PhD student at the University of Gothenburg, Department of Conservation. E-mail: charlotta.bylund-melin@conservation.gu.se

Mattias Legnér is Associate Professor in Conservation at Gotland University, Visby. E-mail: mattias.legner@hgo.se.

Image credits

Figures 1, 2 and 5. Photographer: Charlotta Bylund Melin
Figure 3. Photographer: H. Faith-Ell, 1931

Licence

Development of damage functions for copper, silver and enamels on copper

David Thickett, Rebecca Chisholm and Paul Lankester

Abstract

This paper describes the development of damage functions for silver, copper and enamels using different representative environments in five historic buildings with a wide range of environments.
The copper and silver corrosion rates were determined from Purafill Onguard 3 piezo-electric quartz crystals coated with copper and silver. The thermal deterioration of enamels has been of concern in conservation for some time. Such deterioration, occurring at the metal/glass interface, is difficult to assess visually. Acoustic emission is an extremely sensitive technique that can detect micro-cracking in rigid materials. Its use for enamels has been developed through a series of simple experiments. It was found that events are generated from the development of cracks, as small as 1 micron in length, at the metal/glass interface. A series of experiments in showcases with sensors attached to replica enamels with a conductive gel derived the damaging level of thermal shock, below which acoustic emission was not detected. Replacing the tungsten lighting with LEDs reduced the thermal load and no longer caused acoustic emission. Monitoring of historic enamel plaques (without the gel) replicated these results. Two correlation methods were used to remove environmental noise.

Damage functions are normally developed from periodic measurements of a material's deterioration and a multivariate fit to environmental data. There are questions about how to deal with semi-continuous data such as temperature and relative humidity for this process. Semi-continuous measurement is now available for some damage types such as the Onguard copper and silver piezo-electric quartz microbalances, resistance-based metal sensors and acoustic emission. The high sensitivity of these devices allows data to be collected at the same measurement interval as temperature and relative humidity logging (30 or 60 minutes).

The development of damage functions provides an improved way to assess environmental data. It can allow a move towards more targeted standards, defining equal risk of deterioration, instead of the present prescriptive approach.

Introduction

The interpretation of environmental monitoring data in terms of risk to artefacts is a complex task. In historic buildings, the temperatures, relative humidities and pollution levels are much more influenced by external conditions than in air-conditioned spaces. The fluctuating environments encountered complicate the process significantly. In many institutions this assessment is undertaken by considering published materials science and experiences of the collections' previous response. Damage functions can allow a better-informed assessment and, if

developed under appropriate exposures, can accommodate fluctuating conditions.

Damage functions for copper and silver

Damage functions were investigated for silver and copper in historic house environments. The silver and copper tarnish rates were measured using Purafil Onguard 3 loggers. The Onguard 3 logger uses piezo-electric quartz crystals coated with either silver or copper. The crystals resonate at exactly 6 MHz. As their mass increases the resonant frequency decreases and the mass can be related to the frequency shift by the Sauerbrey equation. Purafil converts the mass increase to a tarnish layer thickness using an averaged tarnish layer composition and density for silver and copper. This technique is known to be temperature sensitive and the Purafil system includes circuitry to compensate for temperature differences. This is reported to be inadequate and a simple numerical correction has been proposed, which was used in this work [1]. The logger also records temperature and relative humidity. The crystals are covered with a perforated clear plastic cover (to physically protect them from handling). This has some impact on dust deposition on to the crystals.

Onguard 3 loggers were placed in seven locations in five properties for three years. The properties were selected to give a range of environments found indoors. The environments are described in table 1.

The properties are in very different environments: relatively polluted, clean, urban, rural and maritime. At Apsley House the different types of mechanical conditioning in rooms give very different environments. The Waterloo Gallery has a full air-conditioning system with activated charcoal filtration, having low pollution levels (compared to the environment). The Plate and China Room has mechanical ventilation with no chemical filtration and has high pollution levels due to the very close proximity of an extremely busy road junction. The Dining Room is naturally ventilated and falls between the two other rooms at Apsley House.

Table 1. Conditions in seven rooms in five properties used for the exposure trials

Location	Amount of time in RH band (%)						Max NO_2 ppb	Max SO_2 ppb	Max O_3 ppb	Max HCl ppb	Max H_2S ppb	Max dust % coverage in 30 days	Max Cl deposition rate mg/m²day
	< 40 %	40–50 %	50–60 %	60–70 %	70–80 %	> 80 %							
Apsley dining room	1.0	41.7	46.7	9.9	0.5	0.0	16.4	0.4	0.7	0.6	0.29	1.34	9.1
Apsley Waterloo gallery	52.8	34.4	12.1	0.7	0.0	0.0	11.6	bd	5.7	1.0	0.02	0.28	1.0
Apsley plate and china room	0.0	57.3	30.9	10.3	1.5	0.0	21.2	0.1	8.9	1.4	0.31	2.13	15.6
Rangers bronze room	16.0	35.9	29.1	12.6	5.5	0.6	8.9		1.9	1.2	0.17	0.16	3.8
Brodsworth dining room	0.0	2.3	18.8	37.5	36.3	5.1	4.2	0.4	12.1	0.8	0.05	0.17	1.6
Audley End dining room	0.0	15.4	48.0	36.6	0.2	0.0	2.0	0.2	5.0	2.0		0.24	1.3
Walmer dining room	1.3	18.7	31.1	20.8	25.4	2.6	3.6	0.2	7.1	0.9	0.13	1.14	94.4

Pollution measurements were taken with diffusion tubes for four 30-day periods, one in each season per year, a total of twelve in the three-year monitoring period. Previous annual measurement campaigns at Rangers House, Chiswick House and Brodsworth Hall (with sequential monthly measurements) had validated this approach as representative of the pollution levels for nitrogen dioxide, ozone, and sulphur dioxide. Figure 1 and table 2 show the data for Rangers House.

The doses calculated from all the data and using one month from each quarter are shown in table 2. The doses calculated from using the four quarterly month periods are within 7.7 % of those calculated from all the twelve months data. This is well within the errors for the diffusion tubes used.

The pollutants nitrogen dioxide, ozone, hydrogen chloride (measured as deposited chloride) and hydrogen sulphide were measured. The method for the commercially available hydrogen sulphide diffusion tube analyses was changed towards the end of the exposures, increasing the detection limit beyond that found in the properties and an alternative method devised by Ankersmit was used [2]. This involved exposing a cleaned silver disc in the end of a diffusion tube. After exposure the amount of silver sulphide on the disc was analysed using cyclic voltammetry [3]. This amount was related to the airborne concentration of hydrogen sulphide using the published empirical calibration.

The monthly silver and copper tarnish rates from the Onguard 3 loggers were regressed against the environmental data using the Minitab software package [4]. The regression equations calculated were for:

Silver

$$Ag = 45.30\ HS + 1.46\ NO + 3.90\ SO + 4.81\ HCl + 0.20\ O_3 + 1.04\ RH + 0.79\ T$$

where
Ag is the silver tarnish rate in Å (0.1 nm) per 30 days
HS is the hydrogen sulphide concentration in ppb
SO is the sulphur dioxide concentration in ppb
HCl is the hydrogen chloride concentration in ppb

O_3 is the ozone concentration in ppb
RH is the mean RH, %
T is the mean temperature, °C

Hydrogen sulphide has a very strong influence on the silver tarnish rate, with hydrogen chloride and sulphur dioxide also having some effect and the other environmental factors less so.

Copper

Cu = 5.71 HS + 0.35 NO +7.30 SO + 2.09 HCl + 1.24 O_3 + 0.17 RH + 1.00 T

where Cu is the copper tarnish rate in Å per 30 days.

Copper tarnished to a much lower degree than silver; hydrogen sulfide has the strongest effect, followed by sulfur dioxide (although it is now present a very low levels in many western European locations), followed by hydrogen chloride, then ozone.

The damage functions cover a wide range of environments (Table 1) and should be suitable for use in many heritage situations. The lack of commercially available carbonyl sulfide sensors or diffusion tubes is limiting. Measurements in museums often detect carbonyl sulfide concentrations around three times the hydrogen sulfide concentration. Figure 2 shows a set of data from a London museum gathered from measurements by Oxford Brookes University with a diffusion tube method.

Although silver is reported to be less sensitive to carbonyl sulphide than hydrogen sulphide, the higher levels mean it is likely to have a significant effect, unconsidered in the damage function. Additionally, dust is known to have a significant effect on silver tarnish and has not been considered in this work due to the design of the Onguard sensors, which significantly reduce dust deposition [5].

The Onguard 3 loggers' batteries failed during some measurement periods over the summers (there is a battery indicator but it appears to be inaccurate at battery levels below 30 %; one logger failed during the exposures and had to be repaired). Hence although the data includes mean temperatures above 20 ºC, there is not a representative amount of data for the higher temperatures. Figure 3 shows the mean temperature plotted against copper tarnish rate. The damage functions derived may not fully account for the higher temperature periods.

Damage functions for enamels on copper

Many of the decay mechanisms of interest result from fluctuations in relative humidity or temperatures. These vary enormously in

Table 2. Annual doses of pollutants calculated from 12 monthly measurements and estimated from subsets of the data

Dose ppm.month	Calculated from all data	Calculated from Jan, Apr, Jul, Oct	Calculated from Feb, May, Aug, Nov	Calculated from Mar, Jun, Sep, Dec
Sulfur dioxide	6.5	6.6	6.0	6.9
Nitrogen dioxide	108.5	108.9	102.8	113.7
Ozone	26.2	26.6	24.7	27.2
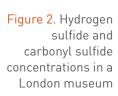
many heritage environments. Figure 4 and 5 show the distribution of daily temperature fluctuation and maximum rate of temperature change for a showcase containing Limoge enamels. The data is taken from a year's monitoring, with some gaps due to poor data transmission of the radiotelemetry system used.

There is a lot of variation in the data. Dealing with different rates of change has been recognised to be important in object response [6,7], but little work has been published on how to process such data.

Enamels are known to be susceptible to damage by temperature fluctuations. De-bonding at the glass/metal interface is particularly problematic as it makes the enamel much more susceptible to further damage. It is also difficult to detect such de-bonding visually.

When rigid materials are flexed, micro-cracks occur. This process is accompanied by acoustic emission, which is high-frequency sound generation. Acoustic emission has been utilised for monitoring wooden furniture and panel paintings and the expansion of sulfate salts in stone [8 to 10]. Application of the technique has been investigated for enamels under thermal stress. Initial work was carried out as part of an MA research project by Jenny Studer between English Heritage and the Royal College of Art and has been reported [11].

Figure 2. Hydrogen sulfide and carbonyl sulfide concentrations in a London museum
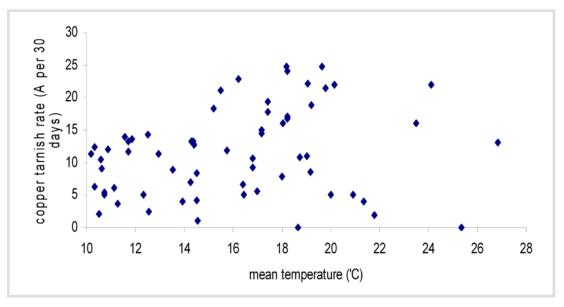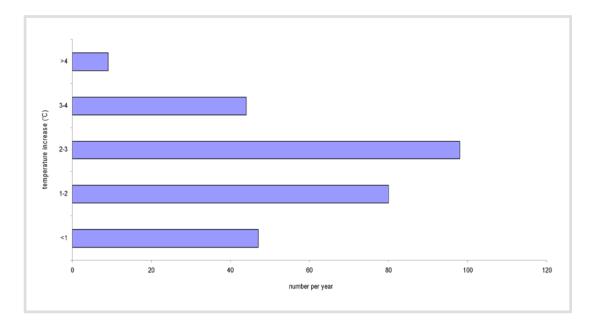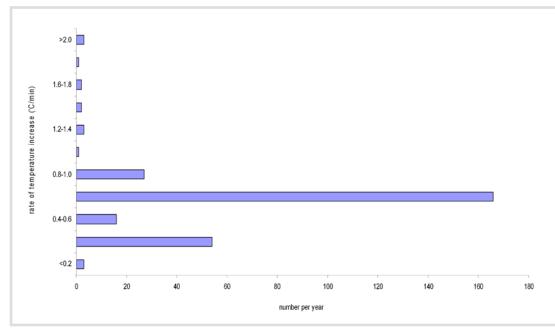
Figure 3. Copper tarnish rates and mean temperatures of measurements used to derive the damage function

Figure 4.
Distribution of daily temperature fluctuations in the Limoge enamel case at Rangers House, London

Figure 5.
Distribution of maximum rate of change of temperature in that case

A physical acoustics Pocket AE2 with R15α (1 kHz to 1 MHz, plus/minus 1.5 dB) sensors was used throughout this work. Simulated weathered enamels were kindly provided by Veerle Van der Linden and Eva Annys, Royal Academy of Fine Arts, University of Antwerp, Belgium. Two sets of experiments were carried out. The enamel pieces with acoustic emission sensors held in contact with rubber bands and with and without a contact gel (Sil-Glyde©) were submitted to three-point bending tests and heating a water bath to 43 °C. The enamel pieces had been pre-weathered and contained several cracks already. In several tests these were marked with black ink and the pieces examined for any new cracks under magnification after the first acoustic emission event in three-point bend tests. The minimum detectable crack length was assessed to be 1.2 μm with the contact gel and 3.1 μm without it. The initial tests had only detected crack lengths of 1.46 mm, indicating the technique would only detect very severe damage, the further tests confirmed its utility to detect the early stages of damage. Acoustic emission was observed in both tests, indicating the method was suitable for monitoring enamels.

Rangers House in Greenwich, London displays the Werner Collection, which includes many Limoge enamels. The collection is on a hundred-year loan to English Heritage. Four showcases contain large numbers of enamels. The custom-built showcases are lit with both fibre-optic and tungsten lighting. The temperature distribution in the narrowest enamel showcase was assessed using eight temperature probes (ACR SR002 loggers with EH-020 A extension probes). Probes were placed in the centre and edge, back and front, top and bottom of the 1.6 m by 1.2 m by 0.4 m case. The edge and centre probes gave very similar readings. A 4.5 K temperature rise at the top front of the case nearest the tungsten lights was recorded, this reduces to 2.7 K at the bottom back. Full details have been published [13]. Thermal imaging (Inframetrics ThermaCam PM290) indicated a temperature gradient of up to 2 K across the surface of some enamels.

Acoustic emission measurements were carried out on both the simulated enamels with contact gel and the objects without contact gel. Experiments with a variety of inert materials showed Melinex sheet (50 µm, non-coated) gave the best (closest to the contact gel) results and this was used between the acoustic emission sensor and glass or metal of the enamels. The deflection of the enamels was measured with a laser transducer (Acuity AR600) to capture the movements causing any micro-cracking. Environmental noise is an issue with acoustic emission and several approaches are available to correct for it. For wood, anti-correlation measurements with two sensors attached to the wood over 6cm apart have been used [8]. The acoustic signal will not travel more than 6 cm in the wood, hence signals measured at both sensors are environmental noise, whereas a signal measured at one sensor only is assumed to be due to acoustic emission from the wood. The signal transmission through copper was measured on a 2 mm copper sheet. This was found to be over 30 cm, larger than most of the Limoge enamel plates being investigated. Two measurement geometries were used.

• One sensor pressed against the enamel glass surface using a g-clamp and Melinex between the sensor and the glass. A second sensor pressed against the backboard of the case (on which the
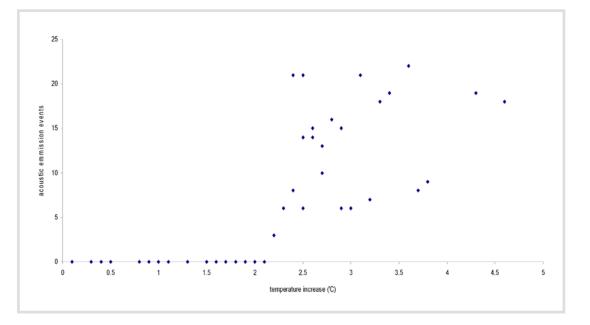

Figure 6. Acoustic emissions from enamel plaque plotted against daily temperature fluctuation

enamels were mounted). Acoustic emission was assumed to originate from the enamel if only the enamel sensor measured a signal.

- One sensor pressed against the front glass of the enamel, a second pressed against the back of the enamel. The difference in measurement time was used to locate where the signal originated from. Experiments with the simulated enamels were used to determine the transit times of signals through the enamel. Shorter time difference signals were assumed to have originated in the enamel.

The measurements showed significant acoustic emission originating from the enamel plaques during the daily heating cycle within the showcases. This evidence was used to argue for funding to change the lighting. The tungsten lamps were replaced with LED lamps. This reduced the temperature gains significantly and there was no longer any detectable acoustic emission, even from the simulated enamel samples with contact gel enhancing the sensitivity of the technique. The daily temperature increase in the showcases with the new lamps was less than 1.4 K.

The data set generated by acoustic emission from the simulated enamels and the temperature profiles causing that emission provide an ideal opportunity to assess threshold thermal fluctuations. Unfortunately, the visual impact of the sensors in front of the enamel plaques limited the duration of these experiments to a couple of daily cycles and most data were from the replica plaques, but some real plaque data were available to check the results. The number of acoustic emissions versus the air temperature increase is plotted in figure 6.

There is a threshold at a temperature fluctuation between 2.1 and 2.5 K (considering the errors in the method). The LED lamps generated daily fluctuations of less than 1.4 K, well below this value.

Surface temperature would be a better measure for this than air temperature, particularly as the tungsten lamps produce an infra-red radiance of 3.3 mW/m^2 at the highest points in the showcases where enamels are displayed. An accurate measurement would require attaching a surface temperature sensor to the front glass of the enamel, which would be visually intrusive for long-term monitoring. Infra-red surface temperature measurement would be extremely difficult for the enamel plaques in the showcases due to the narrow case geometry.

Damage functions with continuous data

Damage functions are normally developed from periodic measurements of a material's deterioration and a multivariate fit to environmental data. The periods tend to be quite long as materials deteriorate slowly and the measurements can be resource-intensive. Pollution data are most often collected using diffusion tubes, exposed for weekly to monthly periods. The difference in period makes the fit for the damage function difficult and pollution data often have to be accumulated. Temperature and relative humidity are normally collected at half-hourly or hourly intervals during exposures. Mean values are generally used for the multivariate fits. Both variables are rarely normally distributed, particularly in indoor environments, therefore using the mean may

be problematic. Additionally, the deterioration of many materials is known to follow parabolic or power laws for relative humidity, and mean values can seriously underestimate the effect [12].

More sensitive analytical methods have been developed and can be used to reduce the period between damage measurements, homogenising the data sets. Semi-continuous measurement is now available for metal corrosion, such as the Onguard copper and silver piezo-electric quartz microbalances and resistance-based metal sensors [14]. The high sensitivity of these devices allows data to be collected at the same measurement interval as temperature and RH logging (30 or 60 minutes). The precision for the Onguard technique is 1 Å, which relates to 10 hours of corrosion in the most aggressive environment measured. The tarnish rates measured for silver varied between 1 A per week and 16.5 A per week. The Onguard 3 output is not precise enough for a regression on a 30-minute time period. However the frequency shifts of the piezo-electric quartz crystals are much more precise with a 1 A increase in silver tarnish equating to a 39 Hz frequency drop. The frequency shift data was extracted from the Onguard 3 loggers and more precise silver and copper tarnish rates calculated.

At four locations in Apsley House and Brodsworth Hall continuous loggers for ozone (Teledyne API M400E), nitrogen dioxide (200EU) and sulphur dioxide (2100E) were located in the rooms with the Onguard 3 loggers for two weeks each. No continuous monitors were available to the project for hydrogen sulphide or hydrogen chloride gases. Hydrogen sulphide continuous analysers can be made by adding a convertor to a sulphur dioxide analyser and fluorometric [15] and lead acetate tape-based analysers are also available. The 30-minute tarnish rates were regressed against the pollution, temperature and RH values as before.

Silver

$$Ag = 0.08\ NO + 0.86\ SO + 0.06\ O_3 + 0.33\ RH + 2.77\ T$$

where
Ag is the silver tarnish rate in Å per 30 days
SO is the sulphur dioxide concentration in ppb
NO is the nitrogen dioxide concentration in ppb
O_3 is the ozone concentration in ppb
RH is the RH, %
T is the temperature, °C

Temperature has a very strong influence on the silver tarnish rate, with sulfur dioxide and RH also having some effect and the other environmental factors less so. The damage function was derived from 5376 measurements, compared with 78 for those derived previously from monthly measurements. Hydrogen sulphide and hydrogen chloride where not measured and hence do not appear in the damage function. It is not possible to compare these short-term damage functions with those derived previously due to this discrepancy.

Copper

$$Cu = 0.01\ NO + 0.35\ SO + 0.30\ O_3 + 0.49\ RH + 0.44\ T$$

where Cu is the silver tarnish rate in Å per 30 days.

RH, temperature, ozone and sulphur dioxide all had similar influences on the copper tarnish rate, nitrogen dioxide much less so and this was only just significant at a 0.05 % level in the regression.

Approaches to uncertainties

The figures produced by damage functions have limited value without an estimate of uncertainty attached. This aspect has not, on the whole, been addressed in the published literature on damage functions. A number of approaches are feasible.

Where large amounts of data are available (such as the real-time measurements described in the 'Damage functions with continuous data' section above, the data can be split into a calibration and verification set. Ideally, the calibration set should range beyond, or at least as far as, the verification set in all the parameters used in the damage function. The values should also ideally be evenly spread over the range. The damage function can be developed from the calibration set and then used with the verification set at each group of variables. The estimated damage can then be compared with the measured damage for that set of values and errors calculated.

Large data sets are often not available due to the relatively long time periods required for accurate object-response measurements. For example, the raw Onguard output could not be accurately used for time periods below three weeks. The monthly data presented has 78 sets of data, which is approaching the bare minimum for the calibration/verification approach. An alternative is to treat the damage function as a multivariate linear calibration. The uncertainty can be estimated from the error estimates in the measurement parameters. In this study plus or minus 0.1 K for temperature, plus or minus 1 % for relative humidity (high accuracy probes were used), plus or minus 6.9 % to plus or minus 10.3 % for the diffusion tube analyses (depending on the gas analysed, this can vary with the method). The error estimates are then combined with the error of the slopes and intercept values from the multivariate calibration to estimate the overall uncertainty at each calculated value.

Further work

The data will be further analysed using the partial least squares method. Correlation between the x-variables (environmental data) can cause multiple linear regression to fail. Environmental data is often collinear and especially so in this instance with high humidity and all the pollutants ingressing from outside the properties. This ingress depends on atmospheric conditions (which influence pressure differences and air exchange rate) and open doors; high air exchange rates will transport all the pollutants. Partial least squares is not sensitive to collinearity and calculates components which effectively describe the covariance structure of the x data matrix [16].

The exposures will be continued for a further year to collect enough summer data. At the end of the exposure period, the tarnished silver and copper crystals will be analysed with x-ray fluorescence spectroscopy and cyclic voltametry to determine the tarnish layer composition. The composition will be compared with

the average value used by Purafil to determine the layer thickness and the values corrected if necessary. The resistance-based Musecorr sensors are about to become commercially available. A subset of the work will be repeated with them to determine the effect of dust deposition on the damage functions.

The acoustic emission method will be trialled with bone and ivory to determine their response to fluctuating relative humidity.

Acknowledgements

References

[1] Ankersmit, B., Watt, S., and Costa, V., 'The use of copper and silver plated piezo-electric quartz crystals to assess indoor air quality', http://www.isac.cnr.it/iaq2004/pdfabstract/ankersmit.pdf (accessed 19 April 2013).

[2] Ankersmit, H.A., Doménech Carbó, A., and Tennent, N.H., 'Tarnishing of silver: evaluation by colour measurements', in Metal 2001: Proceedings of the International Conference on Metals Conservation, ed. I.D. MacLeod, J.M. Theile, C. Degrigny, Western Australian Museum, Welshpool (2004) 157–166.

[3] Costa, V., 'Electrochemistry as a conservation tool: an overview', Conservation Science 2002, ed. J. Townsend, K. Eremin, A. Adrians, Archetype Publications, London (2003) 88–95.

[4] Neter, J., Kutner, M.H., Nachtsheim, C.J., and Wasserman, W., Applied Linear Statistical Models. Irwin, Chicago (1996).

[5] Thickett, D., and Hockey, M., 'The effects of conservation treatments on the subsequent tarnishing of silver', Conservation Science 2002, ed. J. Townsend, K. Eremin, A. Adrians, Archetype Publications, London (2003) 155–161.

[6] Pretzel, B., 'Predicting risks to artefacts from indoor climates', http://www.criterio.biz/icom-cc-lisbon-2011/content/sec-15.htm (accessed 26 March 2012).

[7] Bratasz, Ł., Kozłowski, R., Lasyk, Ł., Łukomski M., and Rachwał, B., 'Allowable microclimatic variations for painted wood: numerical modelling and direct tracing of the fatigue damage', http://www.criterio.biz/icom-cc-lisbon-2011/content/sec-15.htm (accessed 26 march 2012).

[8] Slawomir, J., Bratasz, Ł., and Kozłowski, R., 'Acoustic emission for tracing the evolution of damage', Studies in Conservation 52.2 (2007) 101–109.

[9] Grossi, C.M., Esbert, R.M., Suarez del Rio, L.M., Montoto, M., and Laurenzi-Tabasso, M., 'Acoustic emission monitoring to study

sodium sulphate cristallization in monumental porous carbonate stones', Studies in Conservation 42 (1997) 115–125.

[10] Caneva, C., Pampallona, A., and Viskovic, S. 'Acoustic emission to assess the structural condition of bronze statues. Case of the "Nike" of Brescia', in 26th European Conference on Acoustic Emission Testing (2004) 567–574.

[11] Studer, J., 'Application of acoustic emission technique to Limoges enamels for damage assessment', CeROArt [online], http://ceroart.revues.org/2569?lang=en (accessed 19 April 2013).

[12] Thickett, D., David, F., and Luxford, N., 'Air exchange rate; a dominant parameter for showcases', The Conservator (2006) 19–34.

[13] Tétreault, J., Cano, E., van Bommel, M., Scott, D., Dennis, M., Barthés-Labrousse, M.L., and Robbiola, L., 'Corrosion of copper and lead by formaldehyde, formic and acetic acid vapours', Studies in Conservation, 48.4 (2003) 237–250.

[14] Prosek, T., Kouril, M., Hilbert, L.R., Degres, Y., Blazek, V., Thierry, D., and Hansen M. Ø., 'Real time corrosion monitoring in the atmosphere using automated battery-driven corrosion loggers', Corrosion Engineering, Science and Technology 43.2 (2008) 129–133.

[15] Toda K., Dasgupta P.K., Li, J., Tarver G.A., and Zarus G.M., 'Fluorometric field instrument for continuous measurement of atmospheric hydrogen sulfide', Analytical Chemistry 73.32 (2001) 5716–5724.

[16] Delalieux, F., Cardell-Frenandez, C., Torfs, K., Vleugels, G., and Van Grieken, R., 'Damage functions and mechanism equations derived from limestone weathering in field exposure', Water, Air and Soil Pollution 139 (2002) 75–94.

Authors

David Thickett is Senior Conservation Scientist with the Collections Conservation Team in the National Collections Department of English Heritage. Email: david.thickett@english-heritage.org.uk

Paul Lankester is an Institute of Conservation (ICON) research fellow working in the Collections Conservation Team in the National Collections Department of English Heritage. He is employed on the MEMORI seventh framework project. Email: paul.lankester@english-heritage.org.uk

Rebecca Chisholm is an Institute of Conservation (ICON) preventive conservation intern working in the Collections Conservation Team in the National Collections Department of English Heritage. Email: rebecca.chisholm@english-heritage.org.uk

Licence

Delivering damage functions in enclosures

Paul Lankester and David Thickett

Abstract

A great deal of cultural heritage exists inside enclosures of various kinds. A well-designed enclosure will protect against relative humidity fluctuations and the ingress of industrial pollutants, dust, mould spores and insects. However the concentration of internally-generated pollutants can pose a severe risk to some objects. Performance of enclosures can be difficult to assess, particularly in terms of the risk posed by internal pollutants. Here a decision-support model is developed to apply damage functions and measurement technology to assess enclosures and guide decision makers through the improvements necessary and possible. Case studies are employed to detail the process of the model. The decision-support model will assist and educate collection managers, enabling them to make a decision with the limited information they have available about pollutant mitigation for their collection.

Introduction

Enclosures are often used in cultural heritage to protect collections, often in more than one way. Their primary use is to increase security, but well-designed enclosures can have significant conservation benefits; all enclosures buffer relative humidity (RH) and they are often used to control it. Air-tight enclosures reduce pollution ingress. Well-designed enclosures can prevent corrosion and other pollution-induced damage [1 to 6]. Unfortunately, they can also have adverse effects.

An enclosure can concentrate internally-generated pollutants such as acetic acid, which is often emitted by wood products [2, 7]. Pollutants are commonly found in both historic and modern enclosures, and can cause serious deterioration to certain materials, the most sensitive of which is currently thought to be lead, though there are numerous other examples of materials and pollutants [7].

There are a number of variables that can affect the performance of an enclosure with respect to conservation of historic collections. The most important variable is the air exchange rate (AER) [2, 6]. This controls a number of other factors that can be important in causing damage, such as the concentration of pollutant gases within the enclosure [2].

It is often difficult to assess the performance of an enclosure. In this paper, various options for improving enclosures from the conservation perspective will be described. A decision-support model will be presented to explain the options available to improve performance.

The decision-support model will cover a wide variety of materials, utilising published data on the sensitivity of materials to specific pollutants and damage functions, where available. The model

will also cater for users with different levels of information, from no information all the way through to measured pollution concentrations and air exchange rate measurements.

Pollution

There are a number of airborne pollutants that can have adverse effects on historic collections within an indoor environment [7]. These pollutants can either originate from indoors or outdoors; some pollutant have sources both indoors and outdoors [7]. This classification can be important in understanding the performance of an enclosure. There is a core group of pollutants that are of greatest importance with respect to historic collections. Those that are generated indoors are the carbonyl compounds, alternatively called the organic acids, of which ethanoic (acetic) acid, methanoic (formic) acid and methanol (formaldehyde) are the most common. There are also carbonyl sulfide and hydrogen sulfide that can have both indoor and outdoor sources. Nitrogen oxides, sulphur dioxide

Table 1. Pollutant sources and effects, adapted from [3], and expanded from [7]

Pollutant	Main source		Effects
sulfur containing species, e.g., hydrogen sulphide (H_2S), and carbonyl sulphide (COS)	wool	fabrics, e.g., felt	silver and copper, dyes, photographic materials
	rubber	adhesives	
	some mineral specimens		
organic acids, e.g., formic acid and acetic acid	timber	all, especially oak	lead, copper, zinc, cadmium, magnesium, salt-laden stone and ceramic, shells, paper
	timber composites	MDF, plywood, blockboard, chipboard	
	paints	often oil-based	
	adhesives	polyvinyl acetate, some polyurethanes	
	varnishes		
	sealants	some silicones	
	moth and rot proofing		
	organic materials	specifically those degrading	
formaldehyde	adhesives	urea and phenol formaldehyde	high levels can attack most metals and organic artefacts under suitable conditions
	timber	all	
	timber composites	MDF, plywood, blockboard, chipboard	
	fabrics, paints	Lacks evidence	
chlorides	plastics	PVC, PVDC	copper, aluminium, zinc and iron
	fire retardants	inorganic salts	
nitrogen oxides	plastics	cellulose nitrate	copper and iron, textiles, dyes
	external environment		
sulfur dioxide	some mineral specimens		metals, dyes, paper, textiles, leather, photographic materials
	sulfur vulcanized rubber		
	external environment		
ozone	external environment		rubber, dyes, photographic materials
	office equipment		

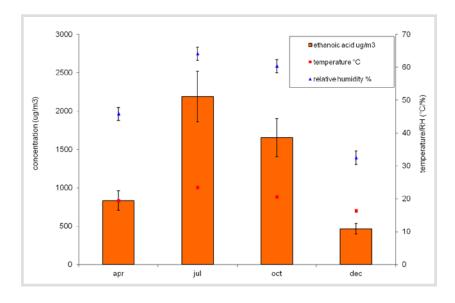and ozone [3, 7] are generally from outdoors. The main pollutants, their sources and effects are shown in table 1.

Environmental monitoring

In order to assess the performance of an enclosure it is useful to understand a number of parameters that can have an effect on some of the variables. For example, the emission rate of a pollutant from a material is related to the temperature and relative humidity of the environment [8]. The temperature and relative humidity are also important for the reaction rate, for example, corrosion will occur faster at higher temperatures and higher relative humidities. Often relative humidity is controlled to a low level to prevent corrosion, for example, unstable archaeological iron is kept below 30 % RH and archaeological copper below 42 % [9]. Therefore monitoring of the temperature and relative humidity is important; ideally the monitoring should be continuous.

It is also useful to measure the concentration of pollutants within an enclosure. This will allow for an assessment of whether the pollutants will pose a risk to specific collections. Pollution measurements are typically carried out over a set period using diffusion-based samplers; it is important that the period measured is representative of the worst environmental conditions. If temperature and RH increase this may result in increased concentrations of pollutants (Figure 1) [8].

The third variable that can be measured, although not environmental, is the air exchange rate of the enclosure; this is the most important variable when assessing the performance of a showcase [2]. The air exchange rate (AER) is important as it will have an effect on the concentration of pollutants within an enclosure [2]. It is important to assess the greatest risk posed to collections in order to determine whether the AER should be high or low; there are examples where each can be beneficial and often decisions need to be considered on a case-by-case basis.

Limited resources and lack of training mean that many organisations will not have measured, or cannot measure all of these variables; therefore, the decision-support model will feature case studies and mitigation options for those without the full range of measurements.

Figure 1. The measured ethanoic acid concentration across a year in an enclosure. Measurements were taken over 30-day periods and are compared to mean temperature and relative humidity
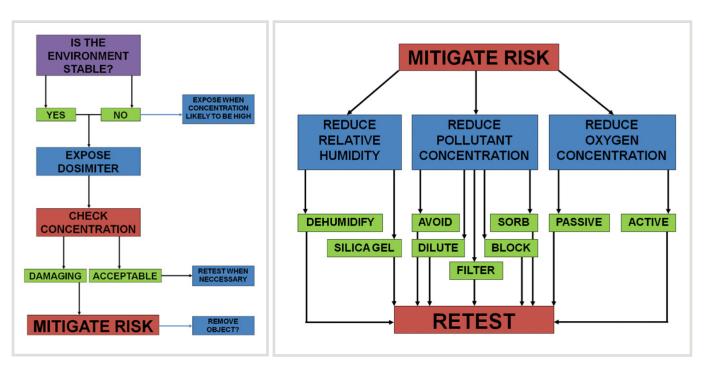
Damage functions

Damage functions, or dose-response functions, relate environmental conditions to material damage [10]. If some of the environment variables are measured it is possible that these can be used with damage functions to estimate whether the current conditions are likely to cause damage, which in turn can indicate whether the enclosure performance is satisfactory or requires adaptation. Examples of damage functions that are useful for collections within enclosures and include pollution data are available. The empirical work of Tetreault for lead and copper can be used to assess concentrations of ethanoic and methanoic acid [11, 12] and RH; the work of Brokerhof for shells with ethanoic acid and RH is also applicable [13]. In this paper the recent work of Fenech [14] will be used, this describes the damage that can be caused to colour photographs, from the combination of temperature, relative humidity and acetic acid concentration. Damage functions are particularly useful, as there are a number of variables to consider, therefore understanding the combined effect of the variables can provide a greater level of knowledge. This may prevent unnecessary adaptation measures where one variable indicates an unacceptable level.

Decision-support model

Lack of information about pollution-induced problems and potential solutions were highlighted as critical impediments in a survey of 117 cultural heritage institutions in 12 countries. Respondents often cited a very dispersed literature as an issue in this area. A decision-support model is being designed to help bring this information together in a simple question-lead form, to set out the available mitigation options for rectifying specific problems. The decision-support model begins with measurement of the environment's corrosivity with the MEMORI dosimeter. However, the model can be used without measurement to explore the adaptation options for improving the performance of enclosures.

Figure 2. Part I of the decision-support model flow chart: pollutant measurement and effect assessment

Figure 3. Part II of the decision-support model flow chart: pollutant mitigation options

The decision-support model will allow addition of new damage functions, which are being defined within the project for the effects of organic acids on varnishes, pigments, leather and parchment, cellulosic materials and textiles, as well as other damage functions which may be derived in the future.

The initial step is the exposure of pollution monitors; there are a number of types available such as the EWO and GSD dosimeters [15, 16], or the MEMORI dosimeter, which is in development and combines the EWO and GSD dosimeters. It is important to expose the dosimeters correctly, and to consider the environmental conditions, whether these are measured or not. The emission of pollutants typically increases with temperature and relative humidity; therefore the dosimeters should be exposed when these variables are at their highest.

Once the pollution dosimeter has been exposed, the results need to be considered with respect to the materials within the enclosure. Some materials are more sensitive than others, and this varies with the pollutant [7]. If the dosimeter response or pollutant concentrations are acceptable then no adaptation is required. Pollutant concentrations should be measured again if conditions change. If the concentration is too high and likely to pose a threat then the object should be assessed immediately and, if necessary, removed from the enclosure. The enclosure should then be assessed and modified to prevent potential for further damage. The process of the decision-support model described thus far is shown as a flow chart in figure 2.

Three main options exist for preventing damage: the concentration of pollutant can be reduced, the relative humidity can be reduced, or the oxygen level can be reduced [7]. The options available are presented in figure 3.

Reduce relative humidity

Higher levels of relative humidity often increase the rate of damage by pollutants. Therefore, reduction of relative humidity should slow rates of damage. If organic materials are present this option should be considered carefully as low relative humidity may cause damage through dimensional changes.

Initially it is important to monitor the relative humidity; depending upon the environment, only spot readings may be necessary. In order to reduce the relative humidity there are two common options, using silica gel or mechanical dehumidification [1]. The first requires a significant volume of gel in the enclosure and a low air exchange rate, the second needs power. Normally, dehumidification has a higher initial outlay of cost; however, this must be balanced against staff time in replacing and reconditioning silica gel. If either method is employed it is important to monitor the relative humidity to ensure it is working effectively.

It is also important to ensure that there is sufficient air circulation between the silica gel compartment and the object space [9]. For this to occur there must be sufficient gaps between the two compartments. Research has found that holes of a 5 mm diameter were not sufficient, whilst 8 mm diameter holes were [9]. Silica gel has a limited lifetime, which will vary depending upon a number of factors, such as the room relative humidity, the air exchange

rate and the moisture buffering capacity of the silica gel [17]. It is possible to calculate the silica gel lifetime.

Dehumidification supplies dry air to an enclosure to reduce the relative humidity. This may require adaptation of the enclosure to allow for connection of an air supply, which can be straightforward but may not always be possible, for example, if enclosures are historic. Different types of dehumidifier are available with different features and requirements.

Reduce pollutants

The second option for reducing the potential threat of damage is to reduce the pollutant concentration. There are five main methods: the pollutants can be avoided, blocked, diluted, filtered or sorbed [7].

Many materials emit pollutants; removing these materials from an enclosure and replacing with tested materials will avoid damaging pollutant concentrations. The standard method for testing materials is the Oddy test [3]. It is important that the Oddy test procedure is followed precisely as described. Unfortunately, removal of emissive materials is not always an option as enclosures may be constructed of the material, and could be historic, in which case another option such as blocking may be more appropriate. New enclosures may be an option. There are a number of important considerations, such as the air exchange rate, the construction materials, the enclosure type, location of doors and hinges, and silica gel capacity and location.

It is sometimes possible to refit an enclosure to improve door sealing or block ventilation pathways to avoid infiltration of external pollutants. Fitting new door seals to ensure a tight seal or adjusting the door to ensure a good fit can be sufficient. It may also be important to test for other gaps, as often they cannot be seen. It is possible to introduce tracer gases within an enclosure, and then use an instrument that detects the tracer gas to identify where leakage paths may exist [12]. This option assumes that the potential damage threat is from outdoor-generated pollutants that infiltrate the enclosure and become concentrated. If the problem is associated with a pollutant that is generated internally, options that increase the AER should be chosen, such as dilution, or alternate methods such as blocking the pollutants.

Another option for reducing the pollutant concentration is to block the emission of the pollutant, this typically concerns pollutants generated within an enclosure [7, 18]. Simple examples include covering wood with moisture barriers such as Moistop; aluminium foils can also be useful as can some lacquers [18]. These solutions should block any emission from entering the enclosure space where objects are stored or displayed. It is important to consider areas that are not visible but could still emit pollutants, for example wooden baseboards should be covered on both sides. Where areas are visible, such as the baseboard within a showcase, it could be covered with a fabric to ensure an acceptable level of presentation; it is important that this fabric has passed the Oddy test. This option is not always applicable as sometimes it can be an object that is emitting pollution. The method of blocking emitting materials is relatively inexpensive, and very effective. It is important, as with all methods of reducing pollution, to re-test the

concentration of pollutants after adaptations have been made, to determine whether the adaptation has been successful or whether further measures may be required.

If internally-generated pollutants are a risk, one option is to dilute the pollutants. To do this the air exchange rate needs to be increased, resulting in a lower concentration of pollutant within the enclosure [18]. One method to increase the AER could be to introduce holes into the enclosure, so that the room air mixes with the enclosure air; however, if the enclosure is historic this may not be an option. An alternative could be to introduce a fan, mixing the air between the room and showcase, diluting the internally-generated pollutant. Typically, the concentration of an internally-generated pollutant within a room is very low, so mixing the two air spaces serves to reduce the concentration [7].

The final method of reducing the pollutant concentration is to remove the pollutant. This can be achieved either through filtration or sorption [7]. Here, filtration is defined as active removal, whereas sorption is a passive method. In filtration, the enclosure air is pumped through a filter that removes the pollution, this will require a power supply. Alternatively, sorbents can be placed within the enclosure to remove the pollution; placement of these sorbents can be crucial [19]. For specific materials such as silver, the sorbents must be placed correctly so that pollutants do not first react with the silver surface, which is very reactive [19]. For example, if there is a known air pathway along a door seal, the absorbent should be placed along that gap [19]. Different types of sorbents include activated charcoal cloth and corrosion Intercept foam amongst others. Some products are pollutant-specific [19]. Again, the AER is important as it will determine the quantity of absorbent required [13]; if the enclosure has a high air exchange rate then more infiltration of externally-generated pollutants will occur and a greater quantity of sorbent may be required.

Reduce oxygen

For some materials a zero-oxygen or anoxic environment will prevent damage from occurring. There are two methods for creating an anoxic environment, either passively or actively. The passive method uses an oxygen scavenger within a very low air exchange rate enclosure [20]. Active systems are now commercially available for showcases. Expert advice is required for this method and it has only been used for the most valued of objects due to the high expense.

Case studies
Kenwood House

At Kenwood House, a property in north London, bookshelf cabinets were converted to display jewellery. The materials used within the enclosure were carefully considered and Oddy-tested. The tested paint for inside the enclosure was not deemed a suitable match to the room paint, which had not been tested, and was then used inside the enclosures. Within two months, very significant corrosion of the jewellery occurred and it had to be removed. Diffusion tube analysis indicated formic acid concentrations of between 3000 and 6000 µg/m^3 and this was attributed to the untested paint [18]. It was therefore necessary to modify the enclosures.

Initially the option chosen was to dilute the concentration. As the enclosure was not historic, it was possible to increase the air exchange rate by drilling holes in the doors at the top and bottom, this takes advantage of the stack effect to maximise the air exchange rate [21]. Following this adaptation, the formic acid concentration was re-tested and was found to have been reduced to between 2000 and 3000 $\mu g/m^3$. This concentration still posed a high risk of corrosion, thus further measures were required. Trials could not find a suitable way to remove the paint. The next approach was to block the emission of formic acid. Sealed MDF (Moistop 622 with 3M 425 tape, covered with a tested fabric) boards were constructed to tightly fit within the enclosure covering the painted surfaces. Re-testing the concentrations of formic and acetic acid indicated levels below the detection limits of 42 and 70 $\mu g/m^3$ respectively. These concentrations are below the lowest reported thresholds for corrosion on any metal.

Corbridge Museum

Corbridge Roman Fort Museum on Hadrian's Wall displays archaeological finds, including a significant collection of archaeological iron. Over 80 iron and copper-alloy objects had to be removed from display due to extensive recent corrosion. Therefore the showcases, which date from the 1990s, required adaptation.

At Corbridge, the air exchange rate of the enclosures was tested, and found to be quite high. Additionally, there was also a baseboard constructed of chipboard. Organic acids are known to accelerate archaeological iron corrosion [9]. The enclosure was refitted, by blocking the emission from the wooden baseboard and sealing all gaps. The baseboard was covered with Moistop and taped to the frame with aluminium foil tape. This blocked air exchange between the object compartment and storage below. The cases were constructed with hollow metal tubing and glass, with a slot running through them. Corrosion Intercept foam was inserted into the metal frame, followed with silicone sealant, which had passed the Oddy test. The AER was significantly reduced. Two plinths were constructed from metal wrapped in a fabric, to hold silica gel. These adaptations allowed the showcase to maintain RH below 30 % for six months and removed the acetic acid. Environmental monitoring was installed to ensure that the silica gel was keeping relative humidity at a safe level.

Another example of reducing the relative humidity was at Battle Abbey, where there is some archaeological iron and copper. The showcases are constructed of a Perspex cover, which is known to be permeable to moisture vapour. A Munters MG50 dehumidifier was installed. This was split between the two metal-containing cases, which required small modifications.

Apsley House

Apsley House is the former home of the Duke of Wellington; it is located in London, beside Hyde Park, but also next to a very busy road. On the ground floor is the plate and china room, where there is a significant collection of silver and gilt objects. These are displayed within large display cases, some of which are historic, but some are more modern additions, in keeping with the historic cases. They are all constructed of wood and glass, and originally contained a woollen felt display fabric. Woollen felt

is known to cause tarnishing of silver [18], presenting the first problem. The location of the room, and its proximity to the busy road is also an issue because of high pollutant concentrations, which were confirmed with measurements within the room [18]. Thus, adaptation of the display cases was required to reduce the potential for silver tarnish.

The first step was to avoid the emissions from the woollen felt; the material was removed and replaced with an Oddy-tested material. In addition to this, to help prevent the ingress of externally-generated pollutants, any gaps were sealed using tested materials, and compression seals were added to each door edge. A leak detector was used to confirm effective sealing of the gaps. These measures resulted in a reduction of the air exchange rate from 5.75 to 0.23 per day, and the silver tarnish rate was reduced by a factor of almost four [18]. Although the tarnish rate was reduced, there was still some potential for damage so filtration has now been installed, which involves the air being pumped through a filter thus removing the pollutants.

Fountains Abbey

A number of lead objects are displayed in a showcase at Fountains Abbey. These were found to be actively corroding, and had to be removed from display. The case required adaption before the objects could be returned. It was found that the display case was largely made from MDF, a known source of organic acids, and specifically acetic acid, which lead is very sensitive to [7]. The concentration of acetic acid was measured using diffusion tubes and found to be above the concentration which would cause damage to lead.

Investigations of the showcase revealed that some sections constructed of MDF were inaccessible, thus removing the option of blocking emissions. In order to display the objects within this showcase it was decided that the showcase air would be diluted. A fan was installed, which works with the case lighting so is in operation during the day and off at night. This fan introduces room air and filters it through corrosion Intercept foam in order to reduce the concentration of acetic acid in the showcase and reduce the potential damage to the lead objects. The concentration of acetic acid was re-tested and found to be at a safe level for lead.

Swiss Cottage Museum

The wooden showcases at Swiss Cottage Museum date from the 1890s. Colour photographs are displayed within them. The concentration of acetic acid was measured at around 2000 µg/m^3. The temperature and relative humidity is in the region of 6 to 23 °C and 60 to 70 % RH. This data was used with the colour photograph damage function [10]:

$$\ln\left(\frac{\Delta E_{RGB}}{t}\right) = 32 + 0.0002\big(c(AA)\big) + 0.01(RH) - 11\left(\frac{1000}{T}\right)$$

This indicates a maximum colour change of 0.014 ΔE_{RGB}/year. Using the unacceptability threshold of Fenech [22], which is 0.43 ΔE_{RGB}/year, this estimates a lifetime of 30 years for the photographs, which was deemed unacceptable in this instance. Adaptation of the showcase was necessary. The effect of acetic acid in the damage

function is very small, hence the decision has been taken to install dehumidifiers directly into the cases in order to reduce the relative humidity to a more acceptable range.

Discussion

The case studies have shown that a mixture of adaptation options is sometimes required as the initial response may not reduce the risk of damage sufficiently. This highlights the importance of re-testing after any adaptation. On occasions where there is a mixture of problems, a solution may be required which combines several complementary adaptations.

Different institutions have different technical capabilities. Some major institutions have almost comprehensive temperature and RH monitoring, a large amount of pollution monitoring and have measured the air exchange rates of many of their enclosures. Many institutions have some temperature and RH monitoring, very little or no pollution monitoring and no facilities to measure air exchange rates. The MEMORI dosimeter is designed to provide a method to address the pollution measurements. Many smaller institutions do not have temperature and RH readings. The model should be designed to cope with these three situations.

Damage functions allow the first situation to develop quantitative modelling of the effect and potential mitigation strategies. Where air exchange rates are not available, a low AER and high AER situation will be modelled. These levels will be set by large numbers of AER measurements on representative types of enclosures, over 300 in total. A series of case studies will be provided with the model for those institutions with no environmental data to allow them to evaluate their situation by comparison with the case studies.

Acknowledgments

References

[1] Thickett, D., Fletcher, P., Calver, and A., Lambarth, S., 'The effect of air tightness on RH buffering and control', in Museum Microclimates: Contributions to the Conference in Copenhagen 19–23 November 2007, ed. T. Padfield, K. Borchersen, the National Museum of Denmark, Copenhagen (2007) 245–251.

[2] Thickett, D., David, F., and Luxford, N., 'Air exchange rate - the dominant parameter for preventive conservation?', The Conservator 29 (2005) 19–34.

[3] Thickett, D., and Lee, L.R., 'The selection of materials for the storage or display of museum objects', The British Museum Occasional Paper 111 (2004).

[4] Schieweck, A., and Salthammer, T., 'Indoor air quality in passive-type museum showcases', Journal of Cultural Heritage 12 (2011) 205–213.

[5] Schieweck, A., 'Emissions from construction and decoration materials for museum showcases', Studies in Conservation 54 (2009) 218–235.

[6] Thomson, G., 'Stabilization of RH in exhibition cases: Hygrometric half-time', Studies in Conservation 22 (1977) 85–102.

[7] Tetreault, J., Airborne Pollutants in Museums, Galleries and Archives: Risk assessment, control strategies, and preservation management. Canadian Minister of Public Works and Government Services, Ottowa (2003).

[8] Thickett, D., Bradley, S., and Lee, L.R., 'Assessment of the risks to metal artifacts posed by volatile carbonyl pollutants', in Metal 98 Proceedings of the international conference on Metals Conservation, ed. W. Mourey, L. Robbiola, James & James, London (1998) 260–264.

[9] Thickett, D., Post Excavation Changes and Preventive Conservation of Archaeological Iron, PhD thesis, School of Biological and Chemical Sciences Birkbeck College, University of London (2012).

[10] Lankester, P., and Brimblecombe, P., 'The impact of future climate on historic interiors', Science of the Total Environment 417–418 (2012) 248–254.

[11] Tétreault, J., Sirois, J., and Stamatopoulou, E., 'Studies of lead corrosion in acetic acid environments', Studies in Conservation 43.1 (1998) 17–32.

[12] Tétreault, J., Cano, E., van Bommel, M., Scott, D., Dennis, M., Barthés-Labrousse, M., Minel, L., and Robbiola, L., 'Corrosion of copper and lead by formaldehyde, formic and acetic acid vapours', Studies in Conservation 48.4 (2003) 237–250.

[13] Brokerhoff, A., and van Bommel, M., 'Deterioration of calcareous materials by acetic acid vapour: a model study', in ICOM-CC Preprints of the 11th Triennial Meeting, Edinburgh, ed. J. Bridgland, James & James, London (1996) 769–776.

[14] Fenech, A., Fearn, T., and Strlič, M., 'Use of design-of-experiment principles to develop a dose-response function for colour photographs', Polymer Degradation and Stability 97.4 (2012) 621–625.

[15] Grøntoft, T., Dahlin, E., Henriksen, J.F., Rentmeister, S., Hanko, M., Heinze, J, Taylor, J., Blades, N,. and Cassar, M., 'An early warning system for organic materials in museums, historic buildings and archives', in Proceedings of the 7th European Conference 'SAUVEUR' Safeguarded Cultural Heritage. Understanding and Viability for the Enlarged Europe, 31 May to 3 June 2006, ed. M. Drdácký, M. Chapuis, Institute of Theoretical and Applied Mechanics of the Academy of Sciences of the Czech Republic, Prague, Vol.1 (2007) 41–50.

[16] Mottner, P., 'Early warning dosimeters for monitoring indoor museum climate: environmental impact sensors and LightCheckTM', in: Strategies for Saving our Cultural Heritage. Papers presented at the International Conference on Conservation

Strategies for Saving Indoor Metallic Collections, Cairo 26–28 February 2007, ed. V. Argyropoulos, A. Hein, M.A. Harith, TEI of Athens, Athens (2007) 53–57.

[17] Weintraub, S., 'Demystifying silica gel', in Object Speciality Group Postprints 9 American Institute for Conservation, Washington (2002) 24–42.

[18] Thickett, D., Stanley, B., and Booth, K., 'Retrofitting old display cases', in 15th triennial conference, New Delhi, 22–26 September 2008: preprints ICOM Committee for Conservation, ed. J. Bridgland, Allied, New Delhi (2008) 775–782.

[19] Thickett, D., and Short-Traxler, K., 'Practical application of sorbents', in Metal 2010: Proceedings of the interim meeting of the ICOM-CC Metal Working Group, 11–15 October 2010, Charleston, South Carolina, USA, ed. P. Mardikian, C. Chemello, C. Watters, P. Hull, Clemson University, Charleston, South Carolina (2011) 414–420.

[20] Makawa, S., Oxygen Free Museum Cases, Getty Conservation Institute, Los Angeles (1998).

[21] Michalski, S., 'Leakage prediction for buildings, cases, bags and bottles', Studies in Conservation 39 (1994) 169–186.

[22] Fenech, A., Lifetime of Colour Photographs in Mixed Archival Collections, PhD dissertation, Centre for Sustainable Heritage, University College London (2011).

Authors

Paul Lankester is an ICON conservation science fellow with the Collections Conservation Team in the National Collections Department of English Heritage. He is currently working on the EU Seventh Framework project MEMORI.
Email: paul.lankester@english-heritage.org.uk

David Thickett is the Senior Conservation Scientist with the Collections Conservation Team in the National Collections Department of English Heritage.
Email: david.thickett@english-heritage.org.

Licence

Stuffing everything we know about mechanical properties into one collection simulation

Stefan Michalski

Abstract

The risk modelling tool Analytica™ has been used to develop a simulation of the fracture probability in a collection of various museum objects exposed to variable and repetitive fluctuations in relative humidity and temperature. The macro part of the model assumes a basic geometry of two attached layers, each with its own response to relative humidity and temperature. It allows the effect of flaws, notches, holes, delamination etc., to be incorporated as variable stress concentration factors. It calculates stress over time using viscoelastic behaviour. The micro part of the model has been developed for paint, based on an adsorbed layer that behaves differently from the bulk, in order to explain the sudden increase in stiffness and decrease in extension before break of high pigment volume concentration (PVC) paints, i.e., oil grounds. All variables in the model can be given a population distribution, and the model calculates final probability of fracture using a Monte Carlo approach, i.e., running the model thousands of times and rolling the dice for each variable each run.

Introduction

Over 25 years ago, Michalski [1] published a review of the mechanical properties of painting materials. In particular, he organized available mechanical data on paints, glues, and varnishes into the standard viscoelasticity model of polymers. Within these generalized maps of glassy, leathery and rubbery behaviour, one could place the particular data on artists' materials generated by our own field, such as that of Mecklenburg [2]. There was an optimism that we had enough knowledge to start modelling stress and fracture in real objects. But neither general models nor the systematic data they needed appeared, only further studies of inadequately characterized paints in special situations.

That situation is changing. Systematic work is beginning to appear on the mechanical properties of well characterized paints by Hagan et al. [3, 4] and moisture isotherm coefficients for many species of wood by Bratasz et al. [5]. This style of research provides the coefficients modellers need.

The model
Models in general

Table 1 outlines the three kinds of model used for mechanical damage. At the two extremes are those most widely used at present: simple damage functions (used widely by others in these proceedings) and complex Finite Element Models, used in engineering research. This paper describes a middle ground using Analytica™ software.

Table 1. Mechanical risk models, from simple to complex

	Damage functions D (RH,T,t)	Analytica	Finite Element Modelling (FEM) with Multiphysics
Complexity	Low complexity	Medium complexity	High complexity
Precision for a specified object	Low precision. Assumes a single universal object	Medium precision for a specified object	High precision for a specified object
Applicability to a varied collection	Poor. Generalizes based on average behaviour of materials and a single simple geometry	Good. Allows detailed distributions for any variables considered significant	Poor. Would require assembling of multiple object models
Labour, expertise, and costs in developing and distributing the model	Low. Easily applied by users without mechanics background. No software costs	Medium. Creating a model requires moderate familiarity with mechanics of materials, and some weeks training in the software (cost ~$1 k). Using a finished model to explore predictions from varied inputs can be performed by non-technical users using free reader software	High. Creating the model requires an expert in mechanics of materials and the software (costs ~$10 k to 50 k) Using finished models to explore predictions from varied inputs requires high expertise and the same expensive software

The physical model of objects in a collection

The physical model (Figure 1) is built on the following assumptions:

- Mechanical vulnerability of an object to humidity and temperature fluctuations can be generalized as the restraint of a weaker component by a stronger component, one or both of which change dimension due to climate fluctuations.
- Stress relaxation over time at various temperatures can be calculated from plots of log (elasticity) versus temperature using the Williams Landel Ferry (WLF) equation.
- The effect of relative humidity (RH) on elasticity and stress relaxation can be calculated by treating moisture as a plasticizer which shifts these plots to a lower glass transition temperature.
- Stress in a viscoelastic system responding to complex fluctuations can be calculated using finite increments of time, treating each increment as a distinct event, calculating stress relaxation for each event, then summing stress from all events using Boltzmann's principle of superposition.
- Fracture of a restrained component occurs when and where stress exceeds strength, or strain exceeds elongation at break, whichever can be computed best.
- Fatigue fracture by a complex mixture of variable cycles can be approximated by a cumulative damage model.
- The variability in vulnerability of objects due to variable materials can be characterized by distributions in each of the relevant material properties.
- The variability in vulnerability of objects due to variable geometry of the restrained and restraining components can be characterized by a distribution in the mechanical parameter called stress concentration.
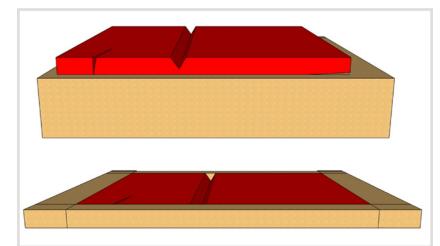
The mathematical model

The software is Analytica™ by Lumina Systems™, widely used in risk analysis. It is designed for scientists who have forgotten their math, and it allows any variable to be given an uncertainty distribution, essential in modelling a collection of variable objects. Figure 2 is the top layer of the fracture model, each of these nodes contains an influence diagram within. Nodes in the final layer contain equations that calculate a value and pass it on to other nodes.

The passage of time in the model

Complex systems such as an object responding to variable climate conditions and simultaneously stress relaxing cannot be solved using a traditional calculus approach. Only the brute force of calculating thousands of small time steps, each dependent on what just got calculated the step before, can predict the outcome. This is the essence of all simulation software.

For the current model, memory in a personal computer limits the number of time steps to about 2000. Fortunately, 2000 steps is just enough to model daily sinusoidal fluctuations (20 steps each) at the
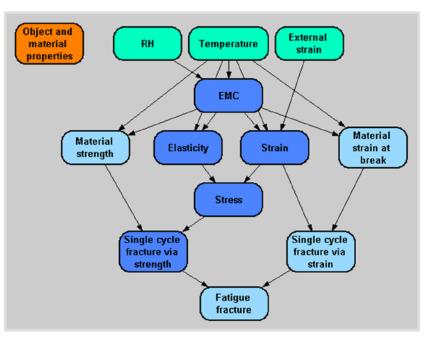
Figure 1. The physical model. A weaker component (red) is restrained by a stronger component (brown). Attachment of the restraining component (brown) can be as a substrate (upper figure) or as a perimeter (lower figure). The restrained component (red) has notches or flaws or a particular geometry that leads to stress concentration

Figure 2. The top layer of the Analytica™ influence diagram. Orange – object and material data; Green – climate and strain inputs; Blue – calculating nodes (pale blue for those incomplete as of January 2013). Arrows from the object and material properties box are not shown for clarity, since they enter almost all the blue nodes

same time as simulating part of a seasonal drift, 100 days. Shock events, such as dropping an object, need a resolution of milliseconds at the beginning of the simulation, but 2000 linear steps would only take the simulation forward a few seconds. To model years of relaxation from a millisecond event, the model is switched to exponentially expanding time units.

Representing object variability in a collection

To explore a collection of variable objects, the model allows the use of a probability distribution in any variable. One then sets a number of runs of the model, for example 1000, and then for each run Analytica randomly selects a value from each of the variables that has been assigned a distribution.

Equilibrium moisture content calculations
Temperature sensitive GAB equation

The most widely used equation for fitting equilibrium moisture content (EMC) data is the Guggenheim-Andersen-de Boer (GAB) equation. Applications in our field to date (and in most of those outside our field) use only the three-parameter GAB equation for data at a single temperature.
Our field, however, is well aware that temperature effects on the EMC isotherm has practical implications: it complicates RH control by buffers during transit, and it complicates retrieval of photographic materials from cold storage. A temperature-dependent GAB equation [6] using activation energies for two of the GAB coefficients was located in the literature, and is used in the model.

Response times of objects

The current model considers each component as having a thermal or moisture capacitance plus an effective surface resistance, i.e., heat transfer coefficient or moisture permeance (close to reality for objects such as coated wood). Heat or moisture transfer for each time step is then calculated using the RH or temperature difference between the outside and the inside of this effective surface. The model recognizes that materials respond slower at lower temperature, the permeance varies with temperature (as does the EMC/RH relation).

A later refinement will be the partitioning of this single block model for RH response into a multi-layer model, so that internal stresses due to gradients can be determined.

Strain calculations
Relative humidity strain

The model uses the calculated EMC to calculate strains due to RH. In isotropic materials, the strain is calculated from volumetric expansion due to EMC. In anisotropic materials, such as wood, specific coefficients for expansion versus EMC in each direction are used.

Thermal strain

The model uses the coefficient of thermal expansion for each material. In the case of polymeric materials, these are themselves

temperature dependent, they are typically twice as high in the rubbery phase as in the glassy phase.

Thermal strain is calculated after the strain due to EMC, i.e., it is the mix of moisture and polymer that responds thermally. Note that for a temperature rise at a fixed RH, the model first adjusts EMC (it drops, the material shrinks) and then it applies thermal effects (the material expands). For paints, the calculation sums the distinct contributions from polymer and pigment.

Elasticity calculations
Effective elasticity of viscoelastic materials

Effective elasticity refers to the stress at some point in time divided by the applied strain. To fit available data exemplified by figure 3, a two parameter sigmoidal function (the logistic function) is used to generate the glassy to rubbery transition. Four more parameters are added to provide the height and slopes of the glassy and rubbery plateaus.
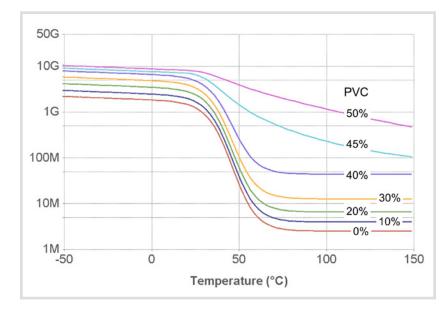
The Williams-Landel-Ferry (WLF) time-temperature superposition equation [7] is used to derive effective elasticity at different times. The three WLF parameters are available for many industrial polymers, and working estimates for oil paints have been based on fits to available data.

Change of effective elasticity with EMC

Moisture can be modelled as just another plasticizer. Plasticizers affect elasticity by shifting the entire sigmoidal plot towards a lower temperature. The equation for the shift uses the EMC together with the plasticizer coefficient of water [7].

The micro model: Effect of pigment volume concentration (PVC) on elasticity

The best systematic data on the effect of PVC on the elasticity of paints versus temperature was compiled by Zosel [8] on acrylic paints. His data provided the benchmark family of plots that the model was built to simulate, and does so in figure 3. Later data by

Figure 3.
Analytica output for modulus of elasticity of acrylic paint at various pigment volume concentrations (PVC)

Hagan et al. [3, 4] on artists' acrylic paints are consistent with this pattern. The model assumes all paints follow the same general pattern of sigmoidal plots, which require eight parameters each. This allows one to fill in partial data sets, such as that of oil paint.
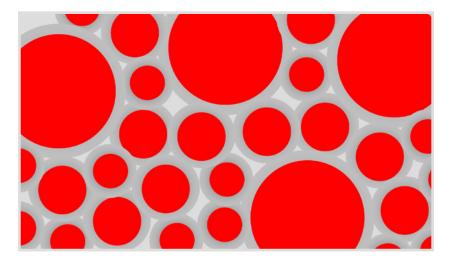
A relatively simple equation in the polymer literature for the effect of PVC below critical PVC (CPVC) was used to fit the set of curves in the glassy region. Later models will extend the model to high PVC using equations of elasticity versus PVC for gessos [9].

The simple equations for the effect of PVC in the glassy region cannot be applied directly in the rubbery region. Zosel [8] proposed an adsorbed layer on pigments particles that acts more as glassy than non-adsorbed polymer. The effective particle becomes the pigment particle plus adsorbed layer, shown in figure 4. Assuming the dependence on the effective PVC in the rubbery region is the same as for PVC in the glassy region, one can deduce the thickness of the adsorbed layer: about 18 % of particle radius for Zosel's TiO_2 in acrylic. This model works for PVC up to 40 %, but fails to fit the very different curve shapes of 45 % and 50 % PVC in the rubbery regime.

Not only are these 45 % PVC and 50 % PVC curves the most problematic to explain, they are the most important to model for fracture prediction in heritage objects. This PVC range is typical of oil grounds and hard gesso, which are responsible for the highest stresses in paintings and polychromes. We suspect that grounds are where most cracks initiate. Our institute's own data on oil paintings dominated by lead white grounds [10] can only be fitted to a long slow transition represented by 50 % PVC in figure 3. No models were found to explain this dramatic change at 45 to 50 % PVC, so the following micro model was developed.

Given the 18 % adsorbed layer estimated earlier for figure 4, one can calculate that the effective PVC of a 45 % PVC paint is 74.3 %. Since the conventional CPVC derived from close packing of spheres of uniform size is 74 %, we find that the 45 % PVC paint has in fact just crossed the close packed threshold for the adsorbed layers. Above this point of coalescence, the paint elasticity is therefore modelled as the original bare pigment particles inside a matrix of adsorbed and much glassier polymer. The effective glass transition of this adsorbed layer is fitted with an exponential dependence on distance for the particle surface. The long slow curves of 45 %

Figure 4. A cross-section of idealized spherical particles at the PVC where the adlayers coalesce. The thickness of the adlayer in the example shown is 18 % of the radius of the largest particles

and 50 % PVC in figure 3 are in effect plots of the glass transition gradient of the adsorbed layer.

Stress calculations
The principle of additive events over time

Boltzmann's principle of superposition [7] allows one to calculate stress from a complex series of incremental strains by calculating the stress independently for each increment and then adding them all together.

In the model, each time step brings a new strain event, an increment of strain which contributes not only its initial stress but also a long slow decay of this stress as it relaxes over all subsequent time steps.

Stress concentration

The use of a stress concentration factor to calculate the increase in local stress due to notches, pre-existing cracks, and odd geometries in general has a long tradition in mechanical engineering. Extensive collections of stress concentration factors are available in handbooks. Modern computations of complex shapes are used to generate even more of these factors.

Fracture calculations
Strength of the material

At the present time, single fixed values of strength in tension and in compression (where available) are entered for purposes of testing the fracture calculation. This node will be modelled in an analogous way to elasticity and figure 3, i.e., as a viscoelastic property dependent on temperature, humidity, and time (strain rate).

Elongation at break

Hagan [3] has shown that elongation at break can be fitted to the same kind of sigmoidal curves as elasticity in figure 3. This node will be modelled using this approach.

Single cycle fracture probability

This node acquires meaning because distributions are entered for variables that affect fracture. For example, if one sets the number of runs of the model to 1000, and there are distributions for PVC and for stress concentration, then the model randomly selects one PVC and one stress concentration (consistent with each distribution curve), runs the model, compares stress to strength, and assigns 1 for fracture, i.e., if stress exceeds strength. This node then counts the number of fractures out of 1000. Figure 8 presents an example of results from this node.

Fatigue fracture

Fatigue data for engineering purposes uses "SN" curves of Stress to cause fracture (Y axis) versus Number of cycles (X axis). See for example Michalski [1] and Koslowski et al. [11]. Data in fundamental studies of fatigue is presented as fatigue crack propagation (FCP) curves, which plot growth of the crack per cycle
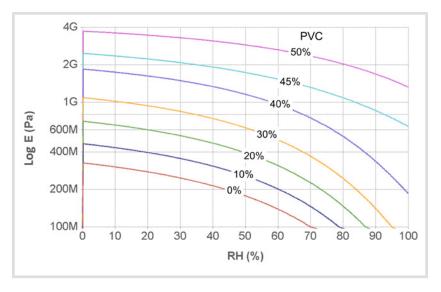
(X axis) versus cycle number. In early work on practical approaches to fatigue in wood structures subjected to complex fatigue loadings, simplified fatigue models used a fractional increment of damage per cycle. The latter will be the basis of this node.

Exploring model predictions to date
The effect of RH on paint elasticity

The model's prediction of the effect of RH on elasticity of oil paint is shown in figure 5. Note that these curves are not taken from elasticity versus RH data, they are predicted by combining:

1. elasticity plots for dry polymer (0 % RH);
2. EMC isotherms for linseed oil films [12];
3. handbook value for the plasticization coefficient of water in polymers.

These predictions can be compared to elasticity versus RH data compiled by Michalski [1] which showed that the best fit to all available data on oil paints of unspecified PVC was a similar curve, where E dropped by a factor of 0.5 between 0 % RH and 70 % RH. For oil paints, the model (Figure 5) gives a factor of 0.53 for 40 % PVC and to 0.48 for 30 % PVC, excellent agreement. Two unexpected predictions emerge from this plasticizer model. First, grounds (PVC of ~50 %) will be affected much less by RH, a factor of only 0.83 between 0 % RH and 70 % RH. This is the result of the adsorbed layer (Figure 4). Second, if the temperature and time conditions place the paint well into the glassy or rubbery plateaus, RH will have little to no effect.

Time shift of an object's response during sinusoidal fluctuations in RH

In a paper by Dionisi-Vici et al., elsewhere in these proceedings, the peak in dimensional response to seasonal RH change in a Viking ship (the Oseberg) is shown to occur approximately one to two months after the peak of summer humidity [13]. Such non-intuitive delays in the response of an object can make it difficult for conservators to correlate the timing of damage with the timing of the humidity data. The idea of RH response time, and its experimental literature is well known, but the examples are all about the response to a sustained step in RH, and not the more

nuanced response to repetitive and approximately sinusoidal fluctuations that occur in reality. We tend to slip back into ignoring the phenomenon when looking for cause and effect in noisy RH charts. This model allows exploration of the delay.

Figure 6 shows the response of various thicknesses of wood to the swing of seasonal RH between summer 70 % RH and winter 30 % RH, with spring taken as time 0. Consider the curve for 8 cm wood, the peak RH at ~90 days causes peak response at ~140 days, so ~50 days delayed. The winter (negative) peaks are 270 days and ~330 days respectively, so ~60 days shifted. This larger winter shift is close to the steady state shift that endless seasons produce when modelled. The first summer cycle here is not fully developed since the values were all set to 0 at this first Spring. The Oseberg ship perhaps has wood ~3 to 4 cm thick, but heavily impregnated, so that diffusion of moisture in and out is several times slower than bare wood, so it behaves as would ~6 to 8 cm of bare wood, so a one to two month delay, as found.

Visual bias when reading the risk from annual and daily fluctuations in RH

Other papers in these proceedings have noted the difficulty in assigning cause and effect when RH fluctuations are a complex mix of seasonal plus short-term fluctuations. Bichlmair et al. (in these proceedings) and others advocate moving average calculations [14].

Figure 7 compares the response to two extreme mixtures of daily and seasonal fluctuations, where the visual judgement of the thermohygrograph chart can be misleading. The lower RH graph looks more risky because our eyes are overwhelmed by the daily fluctuations, but when the model calculates the response of 1 cm of wood coated with a heavy layer of oil paint or lacquer, as in many pieces of furniture, it is the upper RH chart that is more risky, by a factor of 2, because only the change in seasonal average matters. The daily RH wave only causes a small ripple in the object response. Calculating moving averages with different averaging intervals is similar to using a Fourier analysis to obtain the RH fluctuation spectrum over the course of a year, but it has the advantage in detecting rogue waves, big fluctuations caused

Figure 6. Strain in restrained wood (pine, radial) during an annual RH cycle with summer peak 70 % RH and winter trough 30 % RH, at 20 °C, for various thicknesses of wood. Thicker wood responds less, and its peak response is shifted more relative to the RH cycle. Calculated with 2000 time steps, 5 per day. Started with 0 stress at time 0. For simplicity, 1-year RH cycle set to 360 days
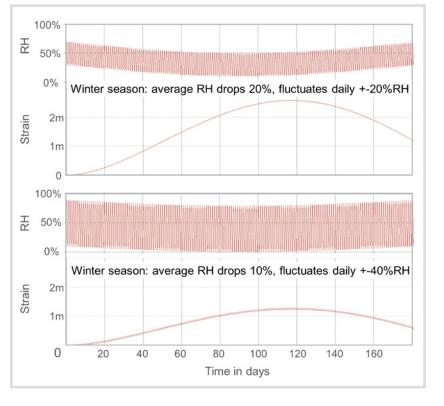
by otherwise random waves falling into sync. No method of RH graph reduction however, can predict risk if one does not know the response time of the object or, in the case of a collection, the distribution of those response times.

Fracture probability and object variability in a collection

Figure 8 illustrates the ability of the model to look at collections of various objects and predict the number of objects that fracture. The objects are layers of oil ground on thick wood (representing polychromes). The paint layer varies in stress concentration, either due to impasto effects, or flaws, or the non-uniformity of the wood grain below the paint. Four different degrees of variability are calculated.

The paint responds partially to the daily fluctuations, fully as the seasonal RH ramps down then up. Response of the wood is slow. For the first 25 days the average tension in the paint is climbing, due to the slow drift down in RH. The wood has not started to shrink itself so as to counterbalance the effect. Tension cracks grow in number between days one and 25, then stop. After 25 days, the shrinkage of the wood becomes significant, average tension in the paint drops, tension cracks stop. At day 50, wood and paint shrinkage are in balance. At day 100, maximum compression is occurring in the paint, although the minimum RH occurred 50 days earlier. Steps in the plot of number of cracks (graph D) result from the actual counting of objects out of 1000. The cracks all result from the long tails of the stress concentration distributions, where stress concentration is greater than 3. The collection with sd = 1.5, i.e., very little variability, very few flaws, has only 5 cracks. The results of figure 8 are preliminary, based on a fixed value of paint strength set at 3 MPa, an estimate taken from Mecklenburg's data for strong oil paints [2], midway between the rapid value (~10 s tests, ~5 MPa) and the equilibrium value (~3 months, ~2 MPa).

Figure 7. Modelling response of heavily coated furniture to daily and seasonal fluctuations. Only half a year is shown, autumn-winter-spring. Zero stress assumed in autumn. Calculated for 1 cm pine, radial, coated with heavy oil paint or equivalent so as to increase response time to many days. Calculated with 3600 time steps, 20 per day. Started with 0 stress at time 0
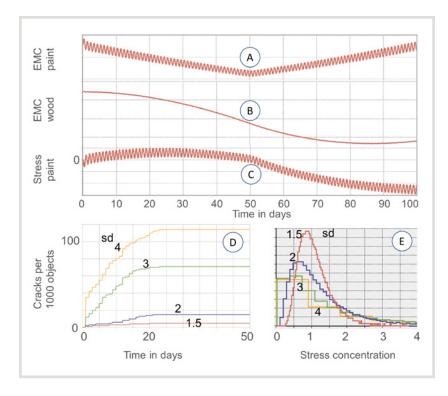
Figure 8. Layer of 200 µm oil paint, 50 % PVC, on 10 cm limewood, radial direction, zero stress in the paint at time 0. For clarity, scales labelled only where essential. Daily sinusoidal fluctuation of plus or minus 10 % RH, plus a slow linear RH change from 50 % RH to 30 % RH over 50 days, then return to 50 % RH next 50 days. Graph A: EMC of the paint layer. Graph B: EMC of the wood. Graph C: Resultant stress in the paint layer across the wood grain. Graph D: Resultant tensile cracks during first 50 days for four different collections of 1000 objects, each collection characterized by a different degree of variability (sd, standard deviation). Graph E: the four distributions of stress concentration used to represent the four different collections in graph D: all are log normal, mean = 1, sd as labelled

Conclusions

A model of a collection of various objects is being built that can calculate the probability of fracture formation during complex climate fluctuations.

The current model uses a fixed strength to calculate fracture probabilities. Until the strength node is built using viscoelastic principles, the fracture calculation is not accurate.

Data is missing for the viscoelastic parameters of aged materials – modulus, strength, elongation at break, all of which are known to change with age. To that end, a Getty Conservation Institute project utilizing newly developed instruments for measuring mechanical properties at the micro scale will play an essential role in providing parameters for the model, so that the predictions are believable [15].

The goal of this model is not the simulation of all objects in complete scholarly detail, it is the search for a level of analysis that is appropriate to practical decisions about managing risk to collections. Once completed, the model can be distributed for others to play 'what if?' with their own collections and risk criteria. (Analytica™ provides free reader software.)

References

[1] Michalski, S., 'Paintings – their response to temperature, relative humidity, shock, and vibration', in Works of Art in Transit, ed. M. F. Mecklenburg, National Gallery of Art, Washington (1991) 223–248.

[2] Mecklenburg, M.F., and Tumosa, C.S., 'Mechanical behavior of paintings subjected to changes in temperature and relative humidity', in Works of Art in Transit, ed. M.F. Mecklenburg, National Gallery of Art, Washington (1991) 173–216.

[3] Hagan, E.W.S., Charalambides, M.N., Young, C.T., Learner, T.J.S., and Hackney, S., 'Tensile properties of latex paint films with TiO_2 pigment', Mechanics of Time-Dependent Materials 13.2 (2009) 149–161.

[4] Hagan, E.W.S., Charalambides, M.N., Young, C.T., Learner, T.J.S., and Hackney, S., 'Viscoelastic properties of latex paint films in tension: influence of the inorganic phase and surfactants', Progress in Organic Coatings 69.1 (2010) 73–81.

[5] Bratasz, Ł., Kozłowski, R., Kozłowska, A., and Rachwal, B., 'Sorption of moisture and dimensional change of wood species used in historic objects,' in Joint Meeting of COST Action IE0601 Wood Science for Conservation of Cultural Heritage and European Society for Wood Mechanics, Braga, Portugal, (2008).

[6] Singh, P.C., and Singh, R.K., 'Application of GAB Model for Water Sorption Isotherms of Food Products,' Journal of Food Processing and Preservation 20.3 (1996) 203–220.

[7] Landel, R.F., and Nielsen, L.E., Mechanical Properties of Polymers and Composites, 2nd edn, Marcel Dekker, New York (1994) 21, 73, 75 and 286.

[8] Zosel, A., 'Mechanical behaviour of coating films', Progress in Organic Coatings 8 (1980) 47–79.

[9] Michalski, S., 'Crack mechanisms in gilding', in Gilded Wood: Conservation and History, ed. D. Bigelow, C.E. Hutchins, Sound View Press, Madison, Conn. (1991) 171–181.

[10] Daly Hartin, D., Hagan, E., Michalski, S., and Choquette, M., 'CCI lining project: testing of lined model paintings from fractions of a second to decades', in ICOM Committee for Conservation, Preprints of the 16th Triennial Conference Lisbon September 2011, ed. J. Bridgland, Criterio, Almada (2011).

[11] Kozłowski, R., Bratasz, Ł., Lasyk, L., and Lukomski, M., 'Allowable microclimatic variations for painted wood: direct tracing of damage development', in Postprints of Symposium 'Facing the Challenges of Panel Paintings Conservation: Trends, Treatments and Training, ed. A. Phenix, A.S. Chui, the Getty Conservation Institute, Los Angeles (2011) 158–164.

[12] Nelson, H.A., and Rundle, G.W., 'Further studies on the physical properties of drying-oil, paint and varnish films', American Society for Testing and Materials. Proceedings 23.2 (1923) 356–368.

[13] Dionisi-Vici, P., Allegretti O., Braovac, S., Hjulstad, G., Jensen, M., and Storbekk, E., The Oseberg ship – long-term hygro-mechanical monitoring in an uncontrolled exhibition environment – preliminary results, see this volume pages 283–297.

[14] Bichlmair, S., Holl, K., and Kilian, R., 'The moving fluctuation range – a new analytical method for evaluation of climate fluctuations in historic buildings', see this volume pages 439–450.

[15] Michalski, D., and Druzik, J., 'The museum environment: a book and coordinated research underway at the Canadian Conservation Institute and the Getty Conservation Institute', poster submitted to Climate for Collections: Standards and Uncertainties Conference, Munich 7–9 November 2012, available at www.doernerinstitut.de.

Author

Stefan Michalski is a Senior Conservation Scientist in the Preservation Services section of the Canadian Conservation Institute, where he has worked for 30 years advising public museums, galleries, archives and libraries on collection risk management, with specializations in lighting and climate. Email: Stefan.michalski@pch.gc.ca

Climate risk assessment in museums

Marco Martens and Henk Schellen

Abstract

To better predict the preservational qualities of indoor climates in museums, a new method is presented to assess risks to museum objects: the specific risk assessment method. The main difference from existing methods is that the object's response time is used to convert the measured indoor climate into the climate as experienced by the object. Four typical, well-defined objects are used in the analysis. For these objects four degradation parameters are determined: biological degradation by means of mould growth, chemical degradation by means of the Lifetime Multiplier and mechanical degradation by means of strain in the construction of an object (usually caused by slower changes in relatively humidity (RH) over time) and also by looking at stresses between construction and decorative layers (usually caused by faster changes in RH).

The outcome of this method of risk analysis is a 4-by-4 matrix (objects versus degradation principles) that contains colours (green for 'safe', orange for 'damage possible' and red for 'damage likely').

The risk assessment method is applied to measurements carried out in various types of museum buildings in the Netherlands and Belgium, with a wide variety of climate systems. Differences in object risks in all these buildings are shown.

It is concluded that the newly proposed risk assessment method is easy to use in the field. It also contains the newest insights in degradation research. In future, it may even be used instead of current climate guidelines such as ASHRAE guidelines.

Introduction

Climate guidelines are used in museums to minimise the damaging effects of temperature and relative humidity. Museum objects might be affected by mould growth. They might also degrade due to changes in the object's materials that are chemical in nature. Moreover objects tend to swell and shrink when temperature and/or relative humidity change over time. This may lead to tension or compression in the object's materials; excessive tension or compression may eventually lead to damage. Current climate guidelines, however, are based on best practice and are very conservative. In a monumental building, trying to achieve an indoor climate that matches these strict climate guidelines is a difficult task which requires large climate systems, irreversible changes to the building and continuous energy consumption.

In the thesis of one of the authors [1] a new method is presented that helps determine the risks of temperature and RH to the deterioration of objects. This paper briefly introduces this method.

Background

Temperature and relative humidity may lead to three types of deterioration. The first, biological deterioration, occurs when temperature and relative humidity are in the growth range of fungi. The second, chemical damage, is associated with the reaction speed of chemical processes which is influenced by temperature and humidity. The third, mechanical degradation, is related to changes in relative humidity (and temperature to a lesser extent), which cause materials to shrink and expand. Each type of deterioration is discussed in more detail below.

Biological degradation

Fungal growth is one of the main deterioration processes in museums across the world. Long-term high relative humidity near surfaces is the cause for fungi to appear. According to Sedlbauer [2] the substrate material plays an important role in determining fungal growth conditions. A model is presented that combines temperature, RH, germination time and growth rate on different substrate types. Temperature, humidity and substrate have to be available simultaneously over a certain period of time in order to trigger fungal growth. This is currently the most extensive model available. Figure 1 displays this so-called isopleths system: a combination of four graphs that determine whether fungal growth can occur and at which growth rate.

The germination time is displayed in the left graphs: the time needed for spores to become active for combinations of temperature and humidity is given. Lines of equal germination time, isolines, are plotted; also a minimum is given which is marked LIM. The graphs on the right display growth rates for combinations of temperature and humidity. Isolines are also given that connect equal rates. The top graphs are valid for surface material type I: biologically recyclable material. The bottom graphs correspond to type II: non-biologically recyclable materials which
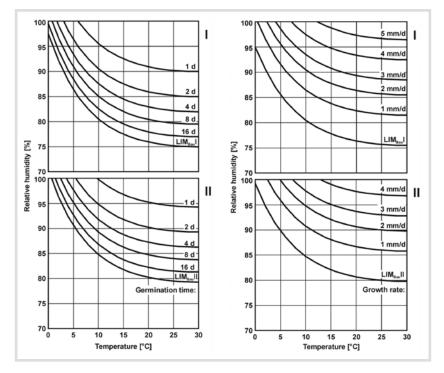

Figure 1. Spore germination time (left) and mycelium growth rate (right) for material category I (biologically recyclable materials) and II (materials with porous structure) [2]

have a porous structure. Type I acts as a nutrient for the fungi directly, while type II is able to capture dust and other particles that can function as a nutrient.

The model is used in this way: once the condition near a surface of type I or II is over the lower germination limit, spores slowly become active fungi. This takes time, which is displayed in the left graph: higher temperatures and higher RH values reduce germination time. Once the fungi become active, growth occurs at a speed corresponding to the right graph. When conditions over the limiting curve do not last long enough to lead to germination, this process stops.

Chemical degradation

Chemical deterioration processes in many objects depend on or are accelerated by water. The amount of water in materials increases as the RH increases, thus increasing reaction speed. This reaction speed decreases at low humidities. Usually the rate of chemical reactions is empirically described by the Arrhenius equation. When comparing measurements on the degradation of paper at different temperatures and relative humidities, Michalski [3] concludes that the Arrhenius equation has to be corrected for low RH by applying a power law in which n equals 1.3. The Lifetime Multiplier (LM) – which is defined as the number of time spans an object remains usable when compared to a condition of 20 ºC and 50 % RH – can be calculated as follows:

$$LM = \left(\frac{50\%}{RH}\right)^{1.3} \times e^{\frac{E_a}{R}\left(\frac{1}{T} - \frac{1}{293}\right)} \tag{1}$$
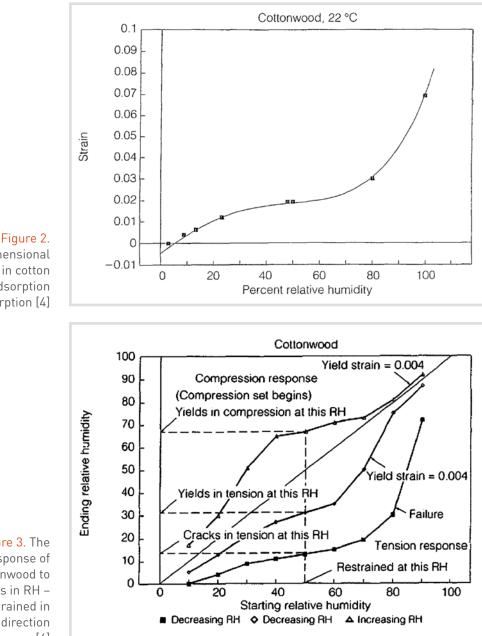
Ea is the activation energy, R the gas constant (8.314 kJ/mol); RH is relative humidity in percent, while T is temperature in Kelvin. The activation energy, the energy that must be overcome for a reaction to occur, depends on the type of materials the object consists of. According to [3], it ranges between 70 and 100 kJ/mol for most materials; 70 for yellowing of varnish and 100 for degradation of cellulose. When looking at formula 1 it can be seen that this activation energy influences the thermal part of the equation, not the hygrical part. The LM is especially important for paper; for other materials such as wood, the risks of chemical degradation are usually small when compared to the risks of mechanical degradation.

Mechanical degradation

Stresses occur in materials due to changes in dimensions or externally applied forces. Stresses lead to fracture when the fracture strength is reached. Stresses larger than the yield point of the material (but smaller than the fracture strength) lead to permanent deformation. Both fracture strength and yield point are material properties and are determined under laboratory conditions. The values are therefore known. In practice, both fracture and permanent deformation need to be avoided to prevent damage and loss of value of an object.
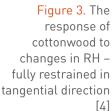
In stable humidity conditions, damage is encountered only if object components are too soft and lack proper support or adhesion or

are too brittle to cope with being handled. When the indoor climate is within the range for normal support of all materials, damage can occur due to fluctuations. For damage prediction, dimensional change for changing RH values is an important material property. Figure 2 shows an example of dimensional change for cottonwood (European poplar); most hygroscopic materials behave similarly.
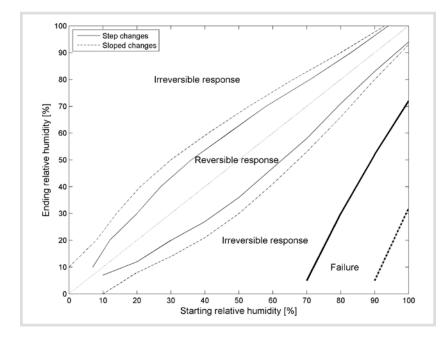
In figure 2, the dimensional change of wood is plotted against relative humidity; The RH was increased from 7 % to 94 % (the material absorbed moisture) and decreased from 94 % to 7 % (now moisture was desorbed). Dimensional change during absorption differs slightly from this behaviour during desorption; also the average curve is given. Smaller absorption and desorption cycles, e.g., from 40 % to 60 % back to 40 % result in a more horizontal graph, thus causing more uniform changes in dimension. For most materials the slope of the graph has its minimum around 50 % RH; near 0 % it is twice as steep and at high RH values even three times. This has two major implications: fluctuations in the middle

Figure 2. Dimensional change in cotton wood for adsorption and desorption [4]

Figure 3. The response of cottonwood to changes in RH – fully restrained in tangential direction [4]

region of RH cause less stress than the same fluctuations in a low or high RH range and if a fluctuation is twice as large the stresses caused by this fluctuation are more than twice as large. Please note that figure 2 only considers wood in the tangential direction; this is the direction in which wood responds the most. In radial direction the response is about half the values presented here; in longitudinal direction responses are small. But the dependence on RH as described above is the same for all directions.

Figure 3 is based on response to a step change in RH of cottonwood. For each combination of starting and ending RH, the resulting damage can be assessed. Changes in the elastic region (in between curves for yield strain = 0.004) do not cause degradation to paintings. Changes in the failure region immediately lead to cracks in materials. In between these regions, plastic deformation occurs which might lead to failure after several RH change cycles. Response time of wood is not taken into account; moreover also fatigue and relaxation are neglected.

Jakieła et al. [5] modelled a lime wood cylinder with a diameter of 13 cm that was in equilibrium with different RH levels. Step and diurnal changes were applied. Dimensional changes and therefore stresses in the wood were calculated; these stresses were related to damage. Figure 4 displays the results. The step changes correspond to the solid lines while the diurnal changes correspond to the dotted lines.

While elastic deformation is considered to be a fully reversible deformation, larger deformation, in the plastic area, can lead to cracking of materials after some time. Bratasz [6] published figure 5, showing which strain leads to cracks in the gesso layer applied to a lime wooden specimen. For lime wood, strains less than 0.15 % do not lead to damage, not even in the long term. A strain of 0.45 % leads to cracking of the gesso after just one cycle. Intermediate strains need a certain number of cycles before the first crack occurs; 0.4 % corresponds to 200 cycles. This means an expected time of 200 years for a first crack to appear in the object if this cycle has a period of one year; if there is a weekly cycle, this time is only four years.

The response time of materials should also be taken into account. Very fast cycles are not noticed by the bulk of the material, so there can be no full response to these cycles. Bratasz [6] published figure 6, in which is shown for two lime wooden panels – 10 and 40 mm thick – which amplitude leads to damage to the gesso layer when taking into account the duration of RH change. A period of 100 years is taken into account, so if the duration of the RH change is one day, there will be 36500 cycles in 100 years; according to figure 5 the corresponding strain is 0.19 %.

The lines in figure 6 have a minimum; very slow changes lead to lower stresses and strains because of relaxation. This also corresponds to figure 5; step changes have a very short period while diurnal changes have a longer period, so diurnal fluctuations can be greater than step changes to cater for an equal amount of damage.
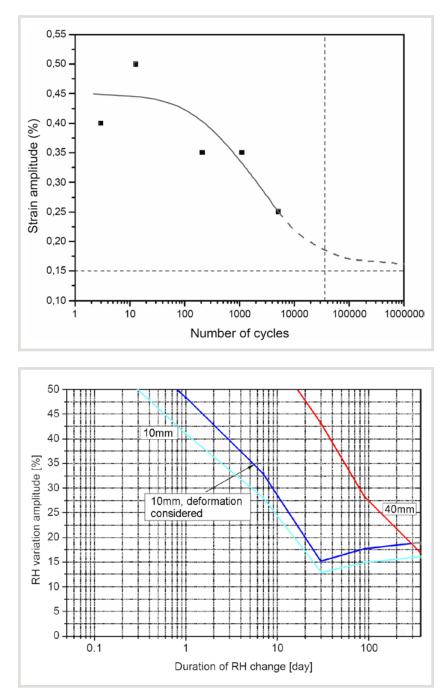
Figure 5. Number of cycles before strain leads to cracking; the horizontal dotted line represents a safe limit for which strain will not lead to damage. The vertical dotted line represents 36500 cycles (daily changes lasting for a century) [6]

Figure 6. RH variations which do not cause damage to gesso on lime wooden panels of 10 and 40 mm thick during a period of 100 years [6]

It is important to note that results displayed in figure 6 are only valid for changes in RH around 50 % RH and for sine signals of constant amplitude and period.

Method

The object-specific risk assessment method consists of a determination of the magnitude of risk for each of the degradation principles for four well-defined objects. Instead of measuring the climate around the object, the climate experienced by the object is taken into account. The response time of an object to changes in RH is used to calculate this experienced climate.

Response time

Objects do not react instantly to changes in RH; it takes some time. Moreover, this response is not linear but exponential. Therefore a definition of response time is needed. It is defined as the amount of time in between the actual change in RH and the object reaching 95 % of that change. The response time can be used to calculate the RH that is actually experienced by the object out of the RH measured close to the object, as:

$$RH_{running,i} = \frac{RH_{running,i-1} + \frac{3}{n} \times RH_i}{1 + \frac{3}{n}} \tag{2}$$

The running average RH at time i is determined by taking the previous running average RH (at i-1) and adding a small fraction of the current RH. This has to be divided by one plus that fraction. The fraction is 3/n, in which n is the number of data points in the response time. The 3 is caused by the choice to take the 95 % value as response time. When the response time is 2 days and hourly values for RH are available, n equals 48.

As you can see, formula (2) greatly depends on the previous value of RH. It is important for a good representation that a longer period is measured than the period analysed. Figure 7 shows the experienced RH for response times of a week, a month and a season.
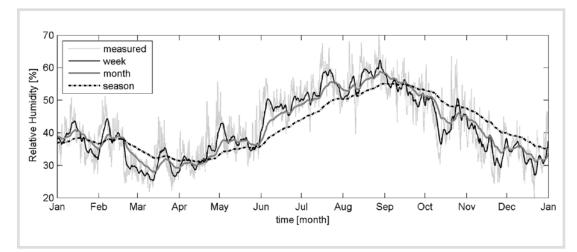

Figure 7. Example of one week response, one month response and three month response to measured RH

Four typical objects

To make an estimate for collection risk out of temperature and relative humidity data, more information about objects is needed. Materials, type of object and construction all play an important role in damage prediction. Objects are needed that are well defined, that represent part of most mixed collections in museums and that have already been researched in the past. Four objects were selected: i) paper; ii) a painting on a wooden panel; iii) a Japanese lacquer box and iv) a wooden sculpture. In this section these objects and their physical properties are described.

For paper objects, biological and chemical degradation are the most important mechanisms, since mechanical damage does not occur unless brittle books are handled without special care. Response times for paper and opened books range from several hours to three days. A single piece of paper responds in minutes, while a book that is placed in a closed cabinet has a response time of six to nine months.
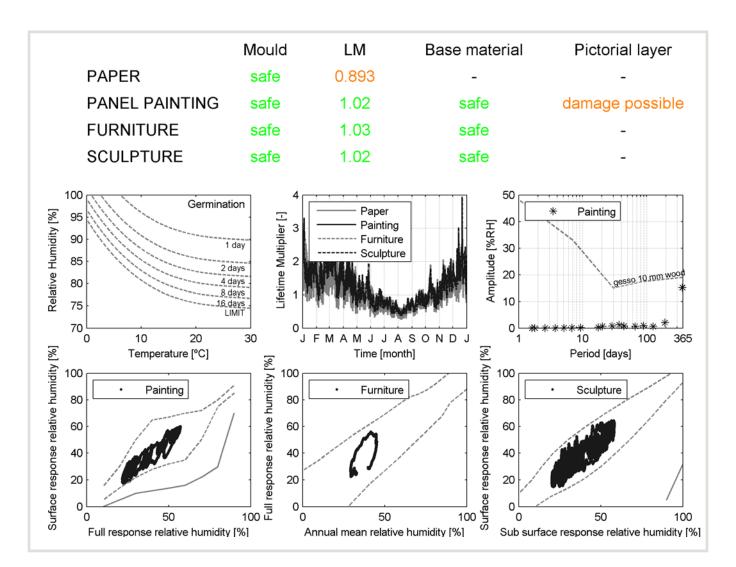
Painted wooden objects consist of various materials: different types of wood, hide glues, gesso composed of glue and gypsum or chalk and different kinds of paint and varnish. Paint itself can include wax, egg tempera, oils or combinations of these. Figure 6 is used to check whether cyclic changes in relative humidity lead to damage to the decorative layer.

Table 1. Analysis method for each object and each degradation principle

| | Degradation | | | |
| | Biological | Chemical | Mechanical | |
	Mould growth	Lifetime Multiplier	Base material	Pictorial layer
Paper	Sedlbauer [2] (Figure 1)	Formula 1, E_a=100 MJ/mol	-	-
Panel painting	Sedlbauer [2] (Figure 1)	Formula 1, E_a=70 MJ/mol	Mecklenburg [4] (Figure 3)	Bratasz [7] (Figure 6)
Furniture	Sedlbauer [2] (Figure 1)	Formula 1, E_a=70 MJ/mol	Bratasz [7] (not displayed)	-
Sculpture	Sedlbauer [2] (Figure 1)	Formula 1, E_a=70 MJ/mol	Jakiela [5] (Figure 4)	-

Table 2. Determination of risks for each degradation principle

	Small risk (green)	Medium risk (orange)	High risk (red)
Biological damage Mould	SAFE Germination factor ≤ 0.2	GERMINATION? Germination factor > 0.2 & Mycelium growth = 0 mm	MM GROWTH Mycelium growth > 0 mm
Chemical damage Lifetime Multiplier	LM > 1	0.5 < LM ≤ 1	LM ≤ 0.5
Mechanical damage Base material	SAFE in elastic region	DAMAGE POSSIBLE in plastic region	DAMAGE LIKELY in failure region
Mechanical damage Pictorial layer	SAFE difference between RH experienced and annual mean < 15 %	DAMAGE POSSIBLE difference between RH experienced and annual mean > 15 %	DAMAGE LIKELY amplitude and period of fitted sine function > 'gesso on 10 mm wood'

	Mould	LM	Base material	Pictorial layer
PAPER	safe	0.893	-	-
PANEL PAINTING	safe	1.02	safe	damage possible
FURNITURE	safe	1.03	safe	-
SCULPTURE	safe	1.02	safe	-

A 1-cm thick piece of wood that is varnished or painted has a hygroscopic halftime of six days, which corresponds to a response time of about 26 days. Near the surface (just under the varnish or paint) the halftime is about one day, corresponding to a response time of 4.3 days.

The Japanese lacquer box is an example of a very delicate piece of furniture. This box was made in 1640. It is the subject of research in the Victorian and Albert Museum in the UK. It was completely restored; its physical properties were examined by Bratasz et al. [7].

There are two areas of restraint in the box. The first restraint corresponds to assemblies of cross-grained wooden elements. Secondly the lacquer is fully restrained in the direction parallel to the grain of the wooden panel it is glued to. In order to minimise degradation, strain in the materials considered should not exceed their yield points in either compression or tension. This yield point is estimated at 0.4 %, the same as in other multilayer components.

Moisture diffusion is not instantaneous; moreover, lacquer acts as an additional barrier for the wooden panel under the lacquer, thus minimizing the risks of short fluctuations in RH; risk of full response by drying or wetting of the entire panel remains. The response time for this full response is about 40 days. Bratasz uses a running average of two months to calculate the experienced RH from the room RH [7].

Figure 8. Example of the specific risk assessment method for a museum

Wooden sculptures are made of one or more pieces of wood, which can be of various types. Most wood carvings are solid. Decorative layers, if applied, are usually thin and open to water vapour. The main problem regarding sculptures is a gradient over the wood. The outer layer responds fast to changes in relative humidity (response time of about 10 hours) while at a few centimetres depth the wood responds very slowly (about 15 days). Differences in moisture content between inner parts and the surface cause stresses in the material. Cracking might occur if stress levels become too high.

Assessing the risks

For each object a slightly different approach is followed. Table 1 provides an overview of the analysis method for each object and type of degradation. Mould growth analysis uses the climate around the object (the room climate). Chemical degradation analysis uses the climate experienced just below the protective layer (varnish). For mechanical damage, both the experienced RH just below the protective layer and the bulk of the material is needed. Table 2 shows how risks are coupled to the analysis of the deterioration types.

Results

Figure 8 shows the result for the specific risk assessment method in a heated room in a monumental building. There is no risk for mould growth on any of the four objects since no data can be found in the germination area (top left graph).

The lifetime multiplier is larger than 1 for three objects; paper objects experience a shorter lifetime because of their higher activation energy. The top middle graph shows that during summer LM is low, while in winter due to low RH the LM is high. When looking at mechanical damage to panel paintings (bottom left graph), furniture (bottom middle graph) and wooden sculptures (bottom right graph) all data points are within the elastic area so risks of mechanical damage are small. Finally, when assessing damage to the pictorial layer of the painting, moderate risks are encountered: there is a yearly fluctuation of more than 15 % in RH, but this does not exceed the line for gesso on 10-mm wood (top right graph).

Figure 9 shows the same result but now in a simplified form. Each level of risk is represented by a colour.
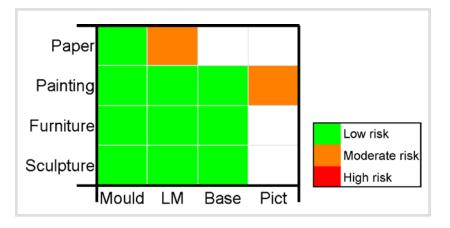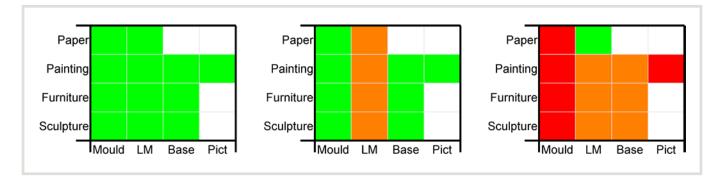

Figure 9. Example of the specific risk assessment method in simple form for a museum

Figure 10. Overview of the climate risks in three different locations: an unheated room (left), a heated and (de)humidified room (middle) and near the envelope in a heated and (de) humidified room (right)

When this method is used in various types of building each using another climate system and set points, differences in risks can be seen instantly. In figure 10, the risks in three locations in two different buildings are displayed.

The left picture shows no risks at all. Yet this is an unheated room in a monumental building which, according to most standards, has an excessively wide temperature range (between 5 and 25 ºC) and a high RH (average 55 %, maximum 68 %). But because of the slowly changing temperature, RH is fairly constant through the seasons and poses little risks to the objects examined.

The middle picture shows increased risks of chemical degradation. In this building, heating, cooling and (de)humidification are used to keep a comfortable temperature (21 ºC) and constant RH (52 %) throughout the year. The chemical degradation is slightly higher when compared to 20 ºC and 50 %, which results in an increased risk.

The right picture shows the indoor climate in the same room as the middle picture, but now in a corner near the monumental envelope. Because of the lower temperatures near the envelope the RH is too high and causes fungal growth. The lower temperature reduces chemical degradation for paper, but risks for the other objects are moderate to high.

This example shows that low-risk indoor climates can exist, sometimes even without the use of climate systems. Moreover, using climate systems with set points that do not match the building and the outdoor climate might cause dangerous climates near the edges of the building envelope.

Conclusions

The specific risk assessment method calculates risks for four objects. The results are easy to interpret: colours indicate the amount of risk for each object. The response time of objects is very important for the determination of the climate experienced by an object. Remember that damaged objects tend to have a shorter response time and therefore react differently from undamaged objects.

Climate guidelines usually are very conservative and based on best practice. By using the specific risk assessment method instead, indoor climates can deviate from these conservative guidelines and still pose little risk to the objects. This opens various opportunities: creating indoor climates that also limit damage to the building, use less energy and/or require less system capacity.

References

[1] Martens, M.H.J., Climate Risk Assessment in Museums, Degradation Risks Determined from Temperature and Relative Humidity Data, Eindhoven University of Technology, Eindhoven (2012).

[2] Sedlbauer, K., Prediction of Mould Fungus Formation on the Surface of and Inside Building Components, Fraunhofer Institute for Building Physics, Holzkirchen (2001).

[3] Michalski, S., 'Double the life for each five-degree drop, more than double the life for each halving of relative humidity', ICOM Committee for Conservation 13th Triennial Meeting, Rio de Janeiro, 22–27 September 2002: preprints, ed. R. Vontobel, Earthscan, London (2002) 66–72.

[4] Mecklenburg, M.F., Tumosa, C.S., and Erhardt, E., 'Structural response of painted wood surfaces to changes in ambient relative humidity', in Painted Wood: History and Conservation, ed. V. Dorge, F.C. Howlett, Getty Conservation Institute, Los Angeles (1998) 464–483.

[5] Jakieła, S., Bratasz, Ł., and Kozłowski, K., 'Numerical modeling of moisture movement and related stress field in lime wood subjected to changing climate conditions', Wood Science and Technology 42 (2008) 21–37.

[6] Bratasz, Ł., and Rachwal, B., 'Computer modelling of dimensional response and stress fields in wooden artworks', presentation to Institute of Catalysis and Surface Chemistry, Polish Academy of Sciences, Krakow, Conference on Allowable Microclimate Variations for Polychrome Wood, Oslo, 18–19 February (2010).

[7] Bratasz, L., Kozłowski, R., Kozlowska, A., and Rivers, S., 'Conservation of the Mazarin chest: structural response of Japanese lacquer to variations in relative humidity', in 5th Triennial Conference, New Delhi, 22–26 September 2008: Preprints (ICOM Committee for Conservation), ed. J. Bridgland, Allied, New Delhi (2008) Vol. II 1086–1093.

Authors

Marco Martens is a private consultant in museum climate management. Email: info@martensklimaatadvies.nl

Henk Schellen is Associate Professor at the Eindhoven University of Technology. Email: h.l.schellen@tue.nl

Licence

The use of computer simulation models to evaluate the risks of damage to objects exposed to varying indoor climate conditions in the past, present, and future

Zara Huijbregts, Marco Martens, Jos van Schijndel and Henk Schellen

Abstract

In the European project Climate for Culture we are trying to evaluate the risks for valuable historical objects exposed to changing indoor conditions due to external climate change. There is an extensive literature on the risks to objects exposed to varying indoor climate conditions. For some well-defined objects, like wooden paintings, experiments and computer simulations have led to descriptions of safe boundary conditions to prevent various types of damage such as mechanical damage. These results, however, have not yet been used in a systematic way to evaluate risks for objects exposed to existing or predicted indoor climate conditions.

Within the Climate for Culture project, we have investigated whether the results from literature can be used to construct so-called damage functions to evaluate the risks for objects. Furthermore, computer simulation models have been used to calculate the expected indoor climate of buildings exposed to a varying outdoor climate. This outdoor climate might be constructed from a historical data file (more than 100 years ago), the present (less than 50 year ago) or predicted future data from outdoor climate prediction computer models (for the next 100 years). The simulated indoor climate will create the input for the risk evaluation. The input might be coupled to damage functions to directly predict the risks for damage to objects. This paper deals with the modelling approach and shows the potential for damage risk evaluation. The historic, present and future indoor climate conditions in a characteristic historic building have been modelled and the damage risk to historical objects has been compared when the building is virtually placed in 468 different locations in Europe. In this way, the impact of future climate change on the indoor climate conditions in a building and the damage potential to its collection can be assessed for areas across Europe.

Introduction

Future outdoor climate scenarios indicate that the outdoor climate is changing and will continue to do so in the near future. This change might greatly affect vulnerable historic buildings and their valuable interiors and objects. In the European project Noah's Ark, the impact of global climate change on European built heritage and cultural landscapes was analysed [1]. This project mainly focused on the damage potential of outdoor climate change to historic building façades. The results indicated that buildings may be at risk in many areas in Europe due to increased amounts of precipitation as well as longer periods of consecutive precipitation. Within the European project Climate for Culture (CfC), we want to assess the impact of climate change on the indoor climate

in historic buildings. We have used outdoor climate data from historical and recent weather files and numerical weather prediction models, provided by our partners in the CfC project, to analyse outdoor climate changes. The outcomes are data files with (hourly) values of the historical, present and future outdoor climate. We had already developed building physical computer simulation models to predict indoor climates of buildings, using (hourly measured) weather data files compiled by meteorological institutes over the past 50 years. For example, Meteonorm [2] provides weather data files for over 100 weather stations across Europe that represent an average climate for that location for a period of one year. Up to now, these data have generally been used to predict the indoor climate and energy use of buildings in the design stage of a building, or later. The impact of future climate change on historic buildings was considered and modelled in a study that compared the future indoor climate within a historic house for several locations in Europe and coupled the results with damage functions for paper and salts [3]. The authors of this article derived a linear transfer function between the indoor and outdoor climate for each month during their research period. However, these transfer functions may not consider variable internal heat loads due to irregular use of shading devices and differences in building use, and the functions cannot accurately take into account climate control systems. With hygrothermal building simulation models it is possible to vary internal heat loads, ventilation rate and climate control set points per hour to obtain an accurate prediction of the indoor climate. Two preliminary studies that used hygrothermal building simulation models to predict the impact of future climate change on two historic buildings in Western Europe and compared the present indoor climate conditions in a historic church for different locations in Europe can be found in [4] and [5], respectively. In the current paper, historical, present and future outdoor predicted climate data are used as input for building simulation models to predict the changing indoor climate in a historic building all over Europe. Based on these predictions we have tried to estimate the possible damage to valuable objects using so-called damage functions. Damage functions are determined by placing objects in a laboratory environment and subjecting them to artificial indoor climate conditions. From the way the object responds (the damage caused to it), we can then predict possible damage to valuable artefacts in the future.

To date, there is little literature providing a coherent approach from outdoor to indoor climate, microclimate and predicted damage on objects. In this paper we attempt to provide and evaluate such an approach. In the next section we will describe the computer simulation method that was used to predict the indoor climate as a result of the outdoor climate and building properties, the meteorological data that were used and the historic reference building that was investigated. We will then go on to describe the damage functions used to evaluate the risk of deterioration of valuable objects induced by indoor climate conditions. Furthermore, we will describe results from one case study using the simulation approach for the indoor climate evaluation in the past, present and future. Finally, the conclusion and discussion will be set out.

Method
Simulation model

The indoor climate simulation model HAMBase [6] was used to evaluate the climate conditions within a historic building. With HAMBase, the thermal and hygric indoor climate and energy use for heating and cooling of multi-zone buildings can be simulated using building material properties, outdoor air temperature and relative humidity (RH), diffuse solar radiation on a horizontal plane, direct normal radiation and cloud coverage. The programme makes use of a standard weather file with boundary conditions for air temperature, RH, wind velocity and direction, solar radiation and cloud cover. These data are usually derived from measured weather data from meteorological weather stations. In our case the data were obtained from the Royal Netherlands Meteorological Institute (KNMI). We made use of hourly measured data from 1960–2012 in a standard format, delivered by KNMI [7]. For these so-called recent past files, the meteorological data already stored are: diffuse solar radiation [W/m^2], air temperature outside [°C], direct solar radiation (plane normal to the direction) [W/m^2], cloud coverage [1–8], RH outside [%], wind velocity [m/s] and wind direction [°]. The indoor climate (derived from HAMBase) is characterised by three properties that are assumed to be uniform in the zone: air temperature, radiant temperature and RH.

Artificially generated historical climate data

To evaluate the effects of climate change over a much longer period, we can make use of historical measured handwritten, and afterwards digitised, weather data. From the KNMI database, ancient climatic data from the 1850s can be obtained for six weather station locations in the Netherlands. These data consist of meteorological data that involve wind directions, wind pressure, temperatures, daily precipitation, surface air pressure, cloud cover and RH which were manually recorded three times a day. However, to use these data in a simulation model we need semi-continuous data with time intervals of an hour. So the manually recorded data had to be interpolated to hourly data. The interpolation was calculated based on hourly data available in the measured data file from KNMI over the years 1971 to 2005: the recent past files. In general, the MATLAB interpolation function balances the smoothness of the missing data in the ancient files with the recent past files. As mentioned previously, the data in the ancient files are based on three time intervals, and the interpolation will estimate the values that are in between these known data points to match the unknown missing data with known data from the recent past files. The data were selected on the basis of a best fit in a period in the recent past files, comparable with the period during the examined year, i.e., with comparable sun elevation and azimuth. The interpolation searched for the same value at certain time within the same time interval of the given available data in the ancient climate file. In this way, historical outdoor climate data files for the years 1881 until 1896 were created. For example, on 1 January 1881, the cloud cover at one of three recorded times was 5. So, in the weather file of 1971 to 2005, also on 1 January, the data would look for the same value of cloud cover of 5 in a comparable time interval. This cloud cover value was used to calculate the ratio of the solar radiation in the historical weather file. The missing hourly values for temperature and RH were calculated by linear interpolation.

Present meteorological data

Meteorological data from the regional climate model REMO of the Max Planck Institute for Meteorology [8] were used to analyse the outdoor climate in Europe. The REMO model is based on the former Europe model: a numerical weather prediction model from the German Weather Service [9]. REMO can be used for weather forecast and future climate simulations on a grid with a minimum horizontal resolution of approximately 10 km. In REMO, climate data from the reference period 1961 to 1990 were used for a control run. The weather forecast, however, could not be predicted for individual days, but it is possible to generate an assumption for the average conditions for an area and the probability and magnitudes of the deviations from this average. The general averaging period is 30 years. REMO data for air temperature, surface temperature, RH, precipitation, wind speed and direction and global radiation were provided with a temporal resolution of one hour. For the evaluation of the present climate, a dataset was composed of climate measurements in multiple weather stations throughout Europe from 1960 until 1990 to represent characteristic climates for the different regions and locations. The meteorological data were then interpolated on a regular grid over Europe. Figure 1 shows an overview of locations and altitudes of the 468 grid points which were used. Some weather locations are located at very high altitudes (> 1000 m). The weather data provided for these locations may considerably differ from weather data from nearby stations at lower altitudes. The Alps and Dolomites are examples of such locations.

Future outdoor climate scenarios

REMO recently produced 'future' outdoor climate scenarios for two 31-year periods: near future (2020–2050) and far future (2070–2100) for all 468 grid locations over Europe. The scenarios were based on the Intergovernmental Panel on Climate Change (IPCC) A1B emission scenario for the period 2001 to 2100 [10]. This emission scenario assumes a world of very rapid economic growth, a global population that peaks in the mid-century and rapid introduction of new and more efficient technologies that balance between fossil-intensive energy sources and non-fossil energy sources.
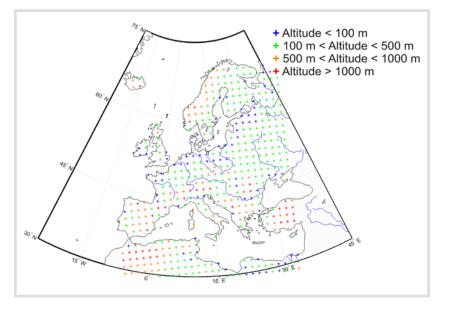

Figure 1. Overview of the locations and altitude of the modelled meteorological datasets on a uniform grid over Europe

Reference building

Three requirements have been defined for the reference building: it has to be a historic building, it has to represent a typical building style that can be found all over Europe and it has to be in use for its original function. A small church near Eindhoven, the Netherlands, was selected (Figure 2). The church, which was built in the nineteenth century, has been registered as a state monument since 1968. The building is frequently used for services, marriages and funerals.
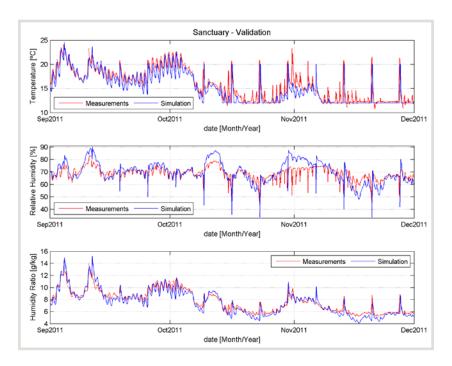
Continuous on-site measurements of the air temperature, surface temperature, and RH at various locations in and around the church were started in March 2011. In addition, measurements of the air exchange rate and heat flow through the walls were carried out. These data were used to validate the HAMBase model. A comparison between the measured and simulated indoor temperature, RH and humidity ratio is presented in figure 3. It should be noticed that in the simulation model, the number of visitors during ceremonies was kept constant and only ceremonies on Sunday morning were taken into account. The simulated temperature generally varied within plus or minus 2 K of the measured temperature, RH was predicted within plus or minus 10 % of the measurements and the humidity ratio was predicted within plus or minus 2 g/kg of the measurements.

Damage functions

Martens [11] developed a new method to assess damage in objects due to the indoor climate. His method is based on the indoor climate an object is experiencing. This climate is derived from the measured indoor climate, using the response time of the object according to:

$$RH_{response,i} = \frac{RH_{response,i-1} + \frac{3}{n} \cdot RH_i}{1 + \frac{3}{n}}$$

(1)

Figure 3. Validation
of the indoor
climate simulation
model of the
sanctuary in the
reference building

The response time is defined as the time needed for an object to react by 95 % to a step change in RH. A 95 % response is defined as 95 % of the end value the object will reach, i.e., $(f_x-f_{start})/(f_{end}-f_{start})$ = 0.95. n equals the number of measured data points in the response time. In the formula $RH_{response}$ of an object at time i is determined by taking the previous $RH_{response}$ at (i-1), adding a fraction of the current RH in the room and dividing by 1 plus that fraction. For a 95 % reaction, the fraction equals 3/n.

Biological degradation

A method of Sedlbauer [12] is used to determine biological degradation by fungal growth. Combinations of temperature and RH determine whether the fungus germinates or grows.

Chemical degradation

The concept of the Lifetime Multiplier (LM) is used here to describe the time an object is usable, compared to a reference indoor condition (20 °C and 50 % RH). Apart from T and RH, the LM also depends on the activation energy, which is a material property [13]. A small risk of chemical damage may occur when LM > 1, a medium risk may occur when 0.75 ≤ LM < 1 and a high risk is predicted when LM ≤ 0.75.

Mechanical degradation

Hygroscopic materials react to changes in RH by absorbing or desorbing moisture from the air. The changes in moisture content imply dimensional changes of the materials. If these materials are not free to expand or contract, stresses occur in the object, which may lead to damage by mechanical degradation. As panel paintings are representative objects in many historic buildings, the hygroscopic and mechanical behaviour of panel paintings have been the subject of a number of extensive studies, e.g. [14 to 16]. In this paper, therefore, panel paintings are chosen as reference objects for mechanical degradation. For this kind of painting, two types of mechanical damage are important: damage

to the wood support and damage to the pictorial layer. Damage to the wood support may occur when the entire object responds to a slow change of RH over time. The dimensional changes of the object may be hindered by the construction of the object and lead to damage, such as cracks. Damage to the pictorial layer may occur when RH variations last longer than the response time of the panel. The moisture content within the panel changes and the object will swell or shrink. As the response of the gesso layer to RH variations is very fast, the mismatch in the response of gesso and the unrestrained wood support can lead to fracturing of the pictorial layer.

Results
Predicted historical indoor climate in the reference building

A prediction of the historical indoor climate in the reference building was generated by combining the indoor climate simulation model with the artificially generated historical climate data as described in the Method section. In the simulation model it was considered that the building remained unheated and that weekly ceremonies on Sunday morning were attended by 50 people on average. The estimated temperature, RH and humidity ratio in the year 1882 are shown in figure 4.

It is predicted that the minimum indoor temperature is slightly below freezing point and that the maximum indoor temperature is around 25 °C. High RH values are predicted: RH remains above 60 % for most of the year and regularly exceeds 90 % in winter.

Present indoor climate in the reference building, virtually placed all over Europe

The calculated meteorological data and damage risks were interpolated to a grid over Europe. The grid used has a resolution of 376 x 226 data points and covers the area between 30 °N to 75 °N and 28 °W to 45 °E. The mean indoor temperature and humidity ratio in the recent past (1960 to 1990) are shown in figure
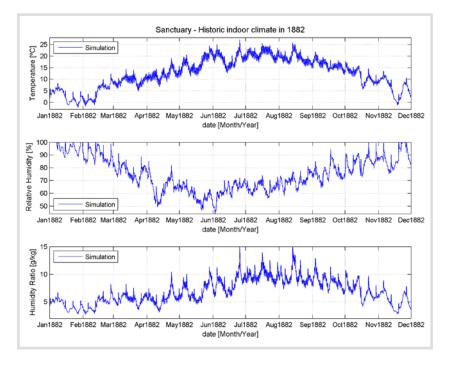

Figure 4. Predicted historic indoor climate conditions inside the church in 1882

Mean indoor temperature [°C]
Recent Past

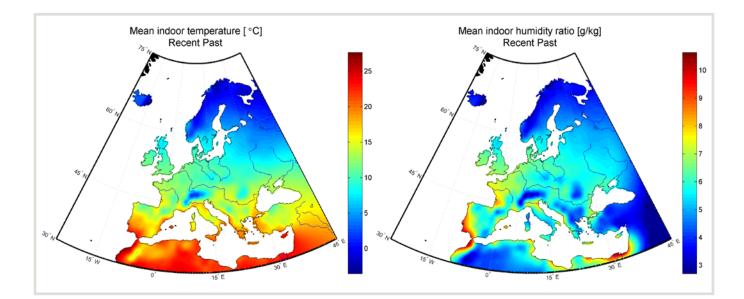Mean indoor humidity ratio [g/kg]
Recent Past

Figure 5. Mean temperature and humidity ratio inside the sanctuary when the church is virtually placed all over Europe

5. The mean temperature inside the church when it is virtually placed all over Europe varies between -4 and 28 °C, while the mean humidity ratio varies between approximately 3 and 11 g/kg. In northern Europe, the average indoor climate in the 31-year period is characterized by low mean temperatures (-4 to 10 °C) and mean humidity ratios varying between 3 to 6 g/kg, which leads to high mean RH values (80 to 90 %). The indoor climate in the Mediterranean area is generally warm (12 to 20 °C) and has a mean humidity ratio of 4 to 7 g/kg inland and 7 to 10 g/kg in coastal areas, leading to a medium mean RH (40 to 60 %). In between, the area around the United Kingdom and Ireland shows a temperate climate (10 to 15 °C) and a medium mean humidity ratio (6 to 7 g/kg) leading to a high mean RH (75 to 80 %).

Future indoor climate in the reference building, virtually placed all over Europe

The impact of future climate change on the indoor climate conditions in the reference building was predicted by calculating the difference in mean temperature and humidity ratio between the recent past, near future and far future. Figure 6a shows that in the near future, the average indoor temperature may increase by approximately 1 K in western Europe and 1.5 to 2 K in southern, eastern and northern Europe. A small increase in the mean humidity ratio is predicted in all areas, varying between circa 0.2 g/kg in southern Europe and 0.5 g/kg in eastern Europe (Figure 6b). Consequently, the mean RH may slightly decrease in most areas, in particular in southern Europe. Larger changes are predicted in the far future: the mean indoor temperature increase in western Europe is approximately 2 K, while a mean indoor temperature rise up to 4 K may occur in northern and southern Europe (Figure 6c, please note that the scale differs from figure 6a as it has been adjusted to the minimum and maximum value in the figure). The predicted mean humidity ratio change is highest in eastern Europe and the coastal areas (1 to 1.5 g/kg) and smallest in Great Britain, Norway and in the inlands of southern Europe (Figure 6d).

Damage functions

The previously described damage functions were used to predict the risks of fungal growth and chemical and mechanical

degradation, based on the calculated indoor climate for the unheated reference building in the recent past, near future and far future. For the recent past weather data, an average amount of mould growth over 100 mm per year is predicted in Great Britain and the coastal areas of western Europe and Scandinavia. Mould growth may considerably increase in near future and far future in and around these areas, while the predicted mould growth risk in southern Europe remains low (Figure 7a). The LM in the recent past is larger than 1.0 for most areas in Europe, except for part of the coastal areas in southern Europe. The LM gradually decreases in the near future and far future, which causes an increased risk of chemical degradation of objects particularly in coastal areas in southern and western Europe (Figure 7b). There is no location in Europe where the indoor climate conditions in the reference building may prevent mechanical degradation of the wood support or pictorial layer of panel paintings. Damage to the wood support is likely in some areas in northern Europe in the three periods, but no consistency is found between the locations where this high damage risk is predicted (Figure 7c). Damage to the pictorial layer is likely
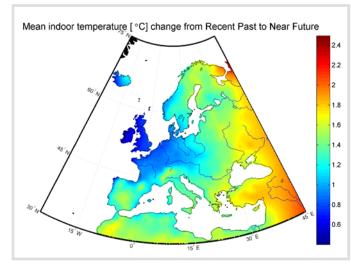

Figure 6a. Mean indoor temperature change from recent past to near future (a positive change means a temperature increase in near future)

Figure 6b. Mean indoor humidity ratio change from recent past to near future (a positive change means an increasing humidity ratio in near future)
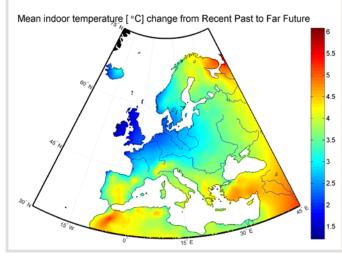

Figure 6c. Mean indoor temperature change from recent past to far future (a positive change means a temperature increase in far future)
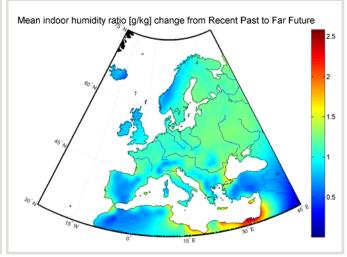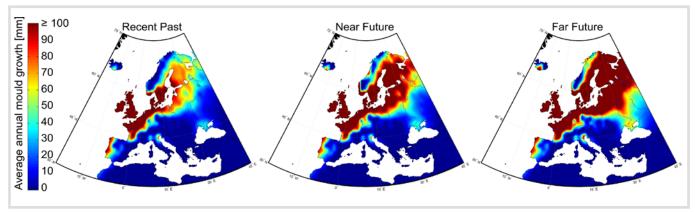
Figure 6d. Mean indoor humidity ratio change from recent past to far future (a positive change means an increasing humidity ratio in far future)

Figure 7a. Predicted average annual mould growth [mm] in recent past, near future and far future
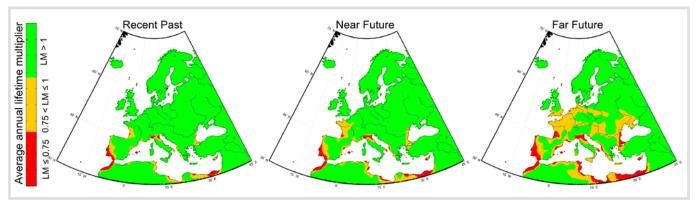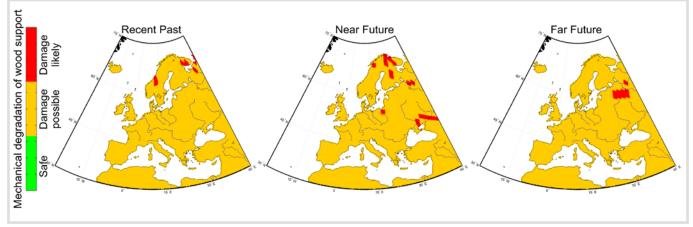
Figure 7b. Predicted average annual lifetime multiplier in recent past, near future and far future

Figure 7c. Predicted mechanical degradation of wood support in recent past, near future and far future
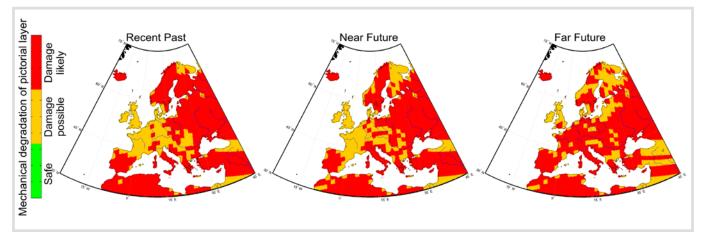
Figure 7d. Predicted mechanical degradation of pictorial layer in recent past, near future and far future

in the recent past and near future in many areas in northern, eastern and southern Europe. In the far future, damage is likely in almost all areas (Figure 7d).

Conclusion and discussion

This study presents a modelling approach to predict the historical, present and future indoor climate conditions in a historic building, when it is virtually subjected to an outdoor climate at various locations across Europe. The predicted indoor climate conditions were calculated from a building simulation model. Based on the predicted indoor climate conditions, the damage potential of biological, chemical and mechanical deterioration were evaluated for the three periods of interest.

The preliminary results show that it seems to be possible to predict the indoor climate conditions and risk for damage in a building over a large area, using regional climate data from the past, present and future. Based on the applied future outdoor climate scenario, a small increase in indoor temperature and humidity ratio is predicted in the near future, while a considerable rise in temperature and humidity ratio may occur in the far future. Damage evaluation shows that there are no places in Europe where no damage to objects is to be expected in the recent past, near future and far future. In cold, humid climates, the risk for chemical degradation is regularly low, while the risk for mould growth and mechanical damage is rather high. In contrast, in warmer dry climates, mould growth risks are rather low, while chemical and mechanical degradation are more important. Climate change may considerably increase the mould growth risk in northern and western Europe. Additionally, a higher risk of chemical degradation may occur particularly around coastal areas in western and southern Europe. No consistent impact of climate change on the predicted mechanical degradation of panel paintings was found.

One of the most critical problems in using this approach is the uncertainty in people's use of the building and its heating, ventilation and air conditioning systems. Also the fact that materials will adapt to the long-term local situation is not taken into account. In addition, the current outdoor future climate scenario is based on only one IPCC emission scenario, which means that there is a high uncertainty in these data. In the near future, more generic building types for different areas in Europe will be selected to acquire more appropriate reference buildings for each location. Furthermore, the microclimate around objects could have an essential influence on the risk evaluation of objects and should be a subject of future research. More objects will be included in the potential damage analysis, e.g., wooden organs, and the impact of climate control systems and climate adaptive measures will also be investigated. The risk maps presented are not yet suitable for climate management in historic buildings, but should be seen as illustrative examples of potential impacts and risks.

Acknowledgements

References

[1] Sabbioni, C., Brimblecombe, P., and Cassar, M., The Atlas of Climate Change Impact on European Cultural Heritage: Scientific Analysis and Management Strategies, The Anthem-European Union Series, London (2010).

[2] Meteonorm, http://meteonorm.com (accessed 10 January 2013).

[3] Lankester, P., and Brimblecombe, P., 'Future thermohygrometric climate within historic houses', Journal of Cultural Heritage 13 (2012) 1–6.

[4] Huijbregts, Z., Kramer, R.P., Martens, M.H.J., Schijndel, A.W.M. van, and Schellen, H.L., 'A proposed method to assess the damage risk of future climate change to museum objects in historic buildings', Building and Environment 55 (2012) 43–56.

[5] Huijbregts, Z., Martens, M.H.J., Conen, C.M.H., Nugteren, I.M., Schijndel, A.W.M. van, and Schellen, H.L., 'Damage risk assessment of museum objects in historic buildings due to shifting climate zones in Europe' in Proceedings of the 5th International Building Physics Conference, 28–31 May 2012, Kyoto, IBPC, Kyoto (2012) 1271–1278.

[6] Wit, M.H. de., HAMBase, Heat, Air and Moisture Model for Building and System Evaluation, Bouwstenen 100, Eindhoven University of Technology, Eindhoven (2006).

[7] KNMI Data Centre, www.knmi.nl (accessed 16 July 2012).

[8] Max Planck Institute for Meteorology, www.mpimet.mpg.de (accessed 16 July 2012).

[9] Majewski, D., 'The Europa-Modell of the Deutscher Wetterdienst' in ECMWF Seminar on Numerical Methods in Atmospheric Models (1991) Vol. l 147–191.

[10] IPCC, Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Core Writing Team, ed. R.K. Pachauri, A. Reisinger, IPCC, Geneva (2007).

[11] Martens, M.H.J., Climate Risk Assessment in Museums, degradation risks determined from temperature and relative humidity, PhD thesis, Bouwstenen 161, Eindhoven University of Technology, Eindhoven (2012).

[12] Sedlbauer, K., Prediction of Mould Fungus Formation on the Surface of and Inside Building Components, Fraunhofer Institute for Building Physics, Stuttgart (2001).

[13] Michalski, S., 'Double the life for each five-degree drop, more than double the life for each halving of relative humidity', in ICOM Committee for Conservation 13th Triennial Meeting, Rio de Janeiro, 22–27 September 2002: Preprints, ed. R. Vontobel, James & James, London (2002) Vol. l 66–72.

[14] Mecklenburg, M.F., Tumosa, C.S., and Erhardt, E., 'Structural response of painted wood surfaces to changes in ambient relative

humidity' in Painted Wood: history and conservation, ed. V. Dorge, F.C. Howlett, Getty Conservation Institute, Los Angeles (1998) 464–483.

[15] Rachwal, B., Bratasz, Ł., Łukomski, M., and Kozłowski, R., 'Response of wood supports in panel paintings subjected to changing climate conditions', Strain 48 (2012) 366–374.

[16] Rachwal, B., Bratasz, Ł., Krzemie´n, L., Łukomski, M., and Kozłowski, R., 'Fatigue damage of the gesso layer in panel paintings subjected to changing climate conditions', Strain 48 (2012) 474–481.

Authors

Zara Huijbregts is a PhD candidate in the Building Physics and Services unit at Eindhoven University of Technology (TU/e). Email: z.huijbregts@tue.nl

Marco Martens is an independent advisor for climate and conservation-related issues in museums, churches and other monumental buildings. Email: info@martensklimaatadvies.nl

A.W.M. (Jos) van Schijndel is Assistant Professor at the Building Physics and Systems Unit at TU/e. Email: a.w.m.v.schijndel@tue.nl

H.L. (Henk) Schellen is Associate Professor at the Building Physics and Systems Unit at TU/e. Email: h.l.schellen@tue.nl

Licence

The application of damage functions to future indoor climate predictions

Paul Lankester, Peter Brimblecombe and David Thickett

Abstract

Predictions of future indoor climate and damage are presented for Knole, a historic house with collections on open display. The process of applying damage functions is discussed, particularly with reference to their application with future climate data, where it is not practical to read off the damage associated with the corresponding temperature and relative humidity from a graph. Results suggest summer months will be warmer but less humid in the future, and winter months warmer and slightly more humid. Damage to paper is predicted to increase, as it the risk of mould growth and insect pest activity. Damaging dimensional change events of wood are predicted to decrease.

Introduction

Damage functions are commonly used in conservation science; they help relate environmental conditions to material damage. These environmental parameters often include temperature, relative humidity (RH) and pollution concentrations. They are particularly useful for assessing an environment for its preservation potential, or the risk of damage it may pose. A typical use of a damage function is to apply it to measured data to predict the level of damage expected to occur. This may be carried out for a number of reasons, for example to assess possible locations for new storage areas, or to understand the potential damage that has been caused to a collection over time.

Recent work, such as that by the NOAH's ARK group and the authors here [1 to 4], has applied damage functions to future climate predictions. It is widely accepted that the future outdoor climate will change. Predictions suggest that temperatures will rise, along with changes in other important environmental variables [5]. Previous work has considered the impact that climate change will have upon cultural heritage outdoors, but it is only recently that the focus has shifted to assessing the possible impact of climate change on the indoor environment [3]. Typically indoor environments are seen as more stable than outdoors but usually the most sensitive objects are stored indoors. Additionally, many historic properties lack active climate control, thus their indoor environments can be heavily influenced by outdoor climates. Therefore, a future changing outdoor climate may impact upon the indoor climate, and collections on open display in historic houses may be susceptible to these changes [3].

Methods

The focus of this paper is to consider the application of damage functions to predicting future damage from a changing indoor environment, however, it is important to describe the process of predicting the indoor climate. To summarise, future outdoor

climate predictions from a climate model are coupled with building simulations to predict the future indoor environment. These predictions can be used in conjunction with damage functions to forecast future damage, and compare how this changes from the baseline.

Climate

Future climate output was taken from the United Kingdom climate projections (UKCP09) weather generator, which uses Hadley model HadCM3 output [6]. The weather generator output has a very high spatial resolution, covering an area of 5 × 5 km, allowing for assessment of specific sites. The output is in the form of statistically plausible daily time series for 30-year periods, there are eight of these 30-year periods. The first is the baseline period, 1961–1990, and this is followed by periods centred in the 2020s, and for each following decade to the 2080s [3, 6]. Climate models are driven by emission scenarios, which describe how emissions will change in the future; due to the uncertainty of the emissions scenarios, a number of possible climate model scenarios are generated. The weather generator has three possible emission scenarios, corresponding to the SRES, which are the scenarios developed by the Intergovernmental Panel on Climate Change: the low (B1), medium (A1B) and high (A1F1) scenarios [7]. The weather generator runs 100 times, allowing for an assessment of the uncertainty of predictions [3]. The scope of the UKCP weather generator is limited to the United Kingdom; previous work has used the underlying Hadley model, HadCM3, to assess locations beyond the UK although this has not been entirely successful [1, 3].

The work in this paper focuses on Knole, a historic house run by the National Trust near Sevenoaks in Kent. Observations of indoor climate (temperature and relative humidity) are available at Knole for the period Jan 2001 to Dec 2009. Unfortunately, as the outdoor observations are incomplete the record from Gatwick (30 km away) was adopted, as it correlates well with the available outdoor observations at Knole [3]. Two rooms at Knole are considered, the Cartoon Gallery and the Leicester Gallery, both contain a mixture of collections and both are unheated spaces.

Building simulation

Typically, building simulation is used for new buildings but it has also been applied to historic buildings previously [8]. Often complex building simulation programmes are used, requiring a considerable amount of parameterisation, which can be problematic. For example, it is not always possible to determine the cross section of a historic wall. In this work it was decided to use a simple transfer function to estimate the indoor temperature and relative humidity. The transfer function mathematically relates the indoor environment and outdoor environment, thus simplifying the building simulation process. One of the drivers behind this was to make building simulation more widely available to heritage organisations, thus the process had to be simpler and easier to define. Complex building simulation models usually require great expertise and usually a building scientist, and even then sometimes assumptions must be used within the models [8]. Although the transfer function is more simple, it is still accurate [3]; in the process of predicting future indoor climate the greatest uncertainty lies in the climate models.

The relationship between the indoor and outdoor environment is described by the simple linear form y = ax+b, where x is the daily outdoor temperature or specific humidity, y the indoor temperature or specific humidity and a and b are the regression coefficients. The transfer function is calculated on a monthly basis to allow for seasonal changes in climate and changes in the pattern of room use [3]. The temperature and specific humidity are combined to estimate the relative humidity. At Knole the prediction of the indoor environment over the nine-year period accounts for more than 90 % of the variance, and gives satisfying indoor predictions [3].

Two rooms from Knole are compared to highlight the individual nature of the indoor environment between two similar rooms in the same building. There are a number of factors such as solar gain and humidity buffering potential that can be different between rooms. Therefore, it is important that the transfer function is applied to each room individually [3].

Damage functions

A number of damage functions applicable indoors are available in the literature [9 to 22], some of which have been used in this project to predict the impact that climate change could have on historic interiors and collections. Damage functions are typically designed for use with current environmental monitoring data, for example, there may be an associated damage value related to a particular set of environmental conditions. Sometimes continuous data can be used although some functions require adaptation if this is to be the case. The use of damage functions with data sets that span centuries can bring additional problems. For example, some paper damage functions use the notion of a lifetime, however when the lifetime is shorter than the period of time considered this can be confusing. Other important considerations are the constants employed in damage functions. The Lipfert damage function of stone recession uses a constant that relates to the concentration of carbon dioxide [23] however, CO_2 levels are predicted to change in the future so this is not appropriate for use in forecasting damage. Care must be taken when using functions to ensure they remain correct [24].

Chemical degradation

This work used four damage functions that estimate damage to paper through chemical degradation. The Isoperm method of Serbera [21] was used, along with the TWPI method of the IPI [20] and the method described by Zou et al. [22, 25]. These three methods follow a similar principle; a fourth method, which attributes greater importance to relative humidity was also investigated, as described by Pretzel [19]. In addition to the paper methods, the recent work of Luxford has adapted the isoperm method for estimating the chemical degradation of silk [14].

These damage functions typically report results as a relative lifetime, however this was changed to a relative degradation rate. The function of Zou et al. uses moisture content instead of relative humidity, as it is the moisture content that actually determines damage. In this case, a moisture sorption curve was utilised to allow relative humidity to be converted into moisture content. It is also worth noting how the damage function normally reports results so this can be taken into consideration. With the Zou et al.

function a lifetime, t, defined as time was used, but nowhere was the unit of time defined. Investigation determined the unit of time to be days. This raises two points. The importance of defining every point of the damage function to allow for its effective use, which is particularly important when constants could change in the future as described earlier. In addition, it is important to understand the unit that is being reported, to enable adaptation of this as required; here a lifetime in years was used, before being converted to a rate.

Salts

For this project, the work of Benevente [10] was used, which estimates the number of thenardite/mirabilite salt transitions that cause damage, defined by exceeding a pressure of 10 MPa. This method determines whether two pairs of temperature and relative humidity change sufficiently to result in the phase change from thenardite to mirabilite, but it also considers the pressure caused to determine whether this is damaging. This method was adapted in the project to investigate other salts. For example, the critical relative humidity of a number of salts is known, and it is possible to determine the critical relative humidity of a mixture of salts [26]. Taking the critical relative humidity at which salts move into and out of solution, it is possible to determine the number of transitions across this critical value, therefore estimating the potential for damage.

Mould

In total, three different mould damage functions were investigated. One of these was split into two parts to investigate the difference between using simply a critical value of relative humidity and the actual process of germination. Critical values below which relative humidity should be maintained are often stated in the preventive conservation literature, when in practice it is possible that these limits can be exceeded and no mould will grow, although other damage mechanisms are likely to become important at high relative humidity levels.

The damage function described by Isaksson et al. predicts the onset of mould growth in two species of wood, spruce and pine [12]. This method developed around the lowest isopleths of mould (LIM) concept of Sedlbauer [27]. The method is based on experimental data, and is adaptable for other materials where data is available, which could be very useful in the conservation of historic materials. The method is designed for use with continuous environmental data, and calculates a running dose. In this work, the number of days where the total dose exceeds the level for germination is reported. This can be simple for annual results, but requires careful consideration for seasonal results as there is a process that builds up to germination so the data must be handled correctly to ensure a valid result. This requires careful consideration when dealing with the large amounts of data associated with climate predictions, and programming that minimises the computation required should be used. For example, a program such as Matlab would take some considerable time to execute these types of calculations, however, a simple programming language that reads one line and does not store that in the memory before moving on to read the next line. could process the associated large amounts of data very quickly. In this work the ancient, but effective, language of AWK was used.

Another method used for predicting mould growth is described by Hukka and Viitanen [11]; this follows a similar method to the Isaksson function, using equations to describe the process of mould germination. The final mould damage function used was that of Moon and Augenbroe [18]. This method is somewhat different from the previous two and required additional work. The method presents a graph of temperature and relative humidity, with five ellipse shapes imposed, defining the number of days until germination. These ellipses are based on experimental data; visual assessment of a pair of temperature and relative humidity allows for classification into one of the groups. From here a method is employed to determine whether enough consecutive days of ideal conditions occur to meet the requirements for germination. For example if the category is defined as requiring two days to germination then two consecutive days of this or a higher category would be sufficient. This method required considerable work to allow for its general use. If there are only a small number of temperature and humidity pairings then it is relatively quick to determine the classification. However, in this work there are millions of pairings of temperature and relative humidity, thus the graph had to be defined computationally to allow for a program to carry out the classification process. The equations of each ellipse were estimated, and incorporated into a program that takes each pair of temperature and relative humidity and determines the highest class to which it belongs.

Dimensional change of wood

A number of different damage functions were also used to estimate the damage to wood caused by dimensional changes. One example was the function described by Michalski [17], which states a number of different humidity fluctuations and the associated vulnerability of wooden artefacts to these fluctuations. To apply this damage function, the change in relative humidity between readings, typically from one day to the next, was counted and reported either monthly or yearly. The humidity fluctuations include 5, 10, 20 and 40 %, with each percentage having a varying degree of associated damage depending upon the vulnerability of the object. The work of Jakiela et al. [13] was also utilised to investigate an additional humidity fluctuation of 30 %.

The research of Mecklenburg et al. was employed as a contrast to the other functions, as despite focusing on wood it also relates to other materials typically found with wood, such as paint [15]. Experimental work has determined the point at which a relative humidity fluctuation causes stresses that exceed the yield point (0.004), thus causing permanent deformation [15]. The point at which the yield point is exceeded can depend on a number of variables, for example, whether humidity is increasing (adsorption) or decreasing (desorption), the orientation of the wood, and the species. Mecklenburg has produced a number of graphs that define the yield points for specific materials and wood species. As these are in the form of line graphs the equation for each section of the line where the gradient is constant was determined. The equations are shown in table 1; these calculations interpret the graph to enable a program to replicate it. The current and previous relative humidity is read by the program, which determines whether this change in relative humidity produces stress that exceeds the yield point. If so, this is read as causing permanent deformation and one damaging event is recorded, which can be reported as required.

As with the mould function, which employed a similar technique, this allows for rapid evaluation of environmental data to determine whether a damaging event may take place.

Degree days

The concept of degree days is to count the number of degrees above a baseline value (here 15 °C was used) and sum these over a period. The concept has been used in a number of disciplines, including heating and ventilation and in relation to pests in the agriculture sector [28] but there has been little use in relation to insect pests in the heritage field. The base temperature was chosen because it is often referenced as the lower temperature limit for insect activity [29, 30]. The majority of insect pests are dependent upon relative humidity, which this method neglects, however there are some species such as the webbing clothes moth and biscuit beetle that do not depend upon the ambient relative humidity. This is particularly important as the webbing clothes moth has recently become a significant problem within the heritage field [31]. Some research has attempted to relate the degree day method to insect pests and an estimation of 490 degree days has been suggested as the requirement for one life cycle of the biscuit beetle (Stegobium panaceum), in comparison to experimental life cycle data [28]. While this does not go as far as predicting the population of a specific insect, or the potential damage that might be caused, it is an indicator for the possible activity of insect pests, which are not dependent upon RH. Further work in this area aims to develop a life cycle model for the webbing clothes moth, to take into account other factors that are neglected using the degree day method.
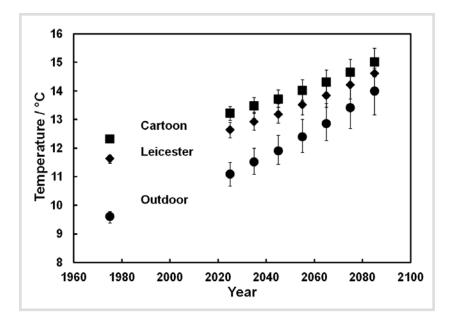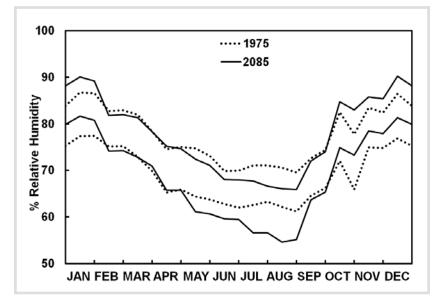
Results
Indoor climate

The predicted impact of climate change on the indoor temperature and relative humidity are shown in figures 1 and 2. The temperature is predicted to rise by 3 K across the century in the Leicester Gallery, less than that predicted outdoors. The temperature indoors is warmer than outdoors, although there is no heating in these rooms, so this is attributed to solar gain [3]. It is evident that assessing individual rooms is important, as each has a slightly different prediction despite the similarity of the spaces. Although not shown here, there is little difference between the future predicted annual average relative humidity of the two rooms compared to the baseline. Each gallery is about 3 % different from the other, with the Leicester Gallery predicted to be more humid. The seasonal prediction of relative humidity is shown, however,

Adsorption		Desorption	
Initial RH	Critical RH	Initial RH	Critical RH
10 ≤ RH ≤ 30	1.5 x RH+1	10 ≤ RH ≤ 30	0.8 x RH-3.33
30 < RH ≤ 40	1.0 x RH+18	30< RH ≤ 50	0.6 x RH+3.33
40 < RH ≤ 50	0.5 x RH+38	50< RH ≤ 60	0.9 x RH-12
50 < RH ≤ 60	0.4 x RH+43	60< RH ≤ 70	2.0 x RH-78
60 < RH ≤ 90	0.8 x RH+19	70< RH ≤ 80	1.6 x RH-50
		80< RH ≤ 90	1.05 x RH-6

Table 1. White Oak critical relative humidity changes for deformation, as [27]

as it was discovered that the annual average which presented little change was hiding a change in seasonality. In future, it is predicted that during summer the indoor environment at Knole will be less humid, and in winter slightly more humid; this could have significant impacts on potential damage.

Damage
Paper

As expected, with the predicted increase in temperature the paper degradation rate increases, resulting in a reduction in lifetime. This is shown in figure 3 for the Cartoon and Leicester Galleries, over the coming century, using the Zou damage function [22]. The predicted change is predominantly driven by the increase in temperature.

Salts

Figure 4 shows the predicted annual average number of thenardite/mirabilite salt transitions that will cause damage over the coming century. A slight decrease is predicted for each room,

but it is difficult to attribute the significance of this change, as it is uncertain how much damage is caused per transition.

Mould

The predicted impact of climate change on mould growth in the two rooms at Knole is shown in figure 5. The predictions are very different in the two rooms: the Leicester Gallery has a high baseline level which increases slightly in the future however, the Cartoon Gallery has a low initial risk. This difference is due to the slight difference between the relative humidity in the two rooms, with one falling below and one above the critical value. This illustrates that even small differences can be significant, thus it is important to assess each room individually. Into the future, the relative humidity changes with season in the Cartoon Gallery so that it crosses the critical value of 75 % more frequently, resulting in an increased mould germination risk. The medians for each period are statistically significant.

Dimensional change of wood
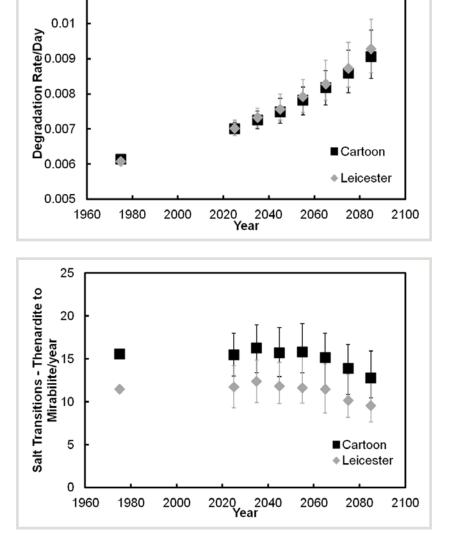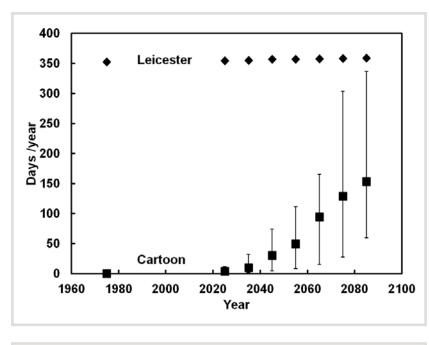
The predicted shift in dimensional change events to wood is shown in figure 6 as a seasonal change. As an annual average, this
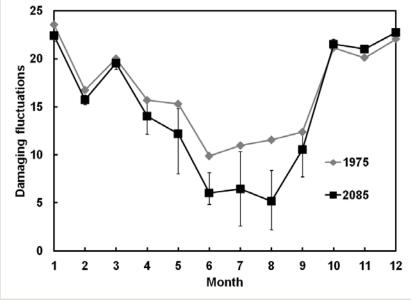
Figure 3. Predicted annual average chemical degradation rate of paper as described by the Zou damage function. For the Cartoon and Leicester Galleries at Knole, from 1960–2100. The error bars represent the interquartile range

Figure 4. The predicted impact of climate change on the number of damaging thenardite/ mirabilite salt transitions in the Cartoon and Leicester Galleries at Knole. The error bars represent the interquartile range

Figure 5. The predicted impact of climate change on the risk of mould growth in the two galleries at Knole, as described by the Isaksson damage function. Error bars represent the interquartile range

Figure 6. The predicted seasonal shift in damage to wood caused by dimensional changes, for the baseline and far future periods in the Cartoon Gallery at Knole. Error bars represent the interquartile range

damage function predicts a decrease in the number of damaging events. Figure 6 indicates that this is due to changes in the spring and summer months, when the relative humidity is predicted to be lower in the summer. In relation to the damage function, a lower relative humidity moves towards a safer region, where a greater fluctuation in relative humidity is allowed before damage occurs from stresses that exceed the yield point.

Degree days

The cumulative number of degree days for the baseline (1975) and far future period (2085) is shown in figure 7. This demonstrates that the annual total for the baseline period is surpassed before the end of July in the far future. The annual number of degree days in the far future (900) is more than double the value for the baseline period (370). This is likely to lead to an increased number of lifecycles for insect pests such as the webbing clothes moth and biscuit beetle, which are virtually independent of relative humidity. This may result in increased populations and potentially a greater
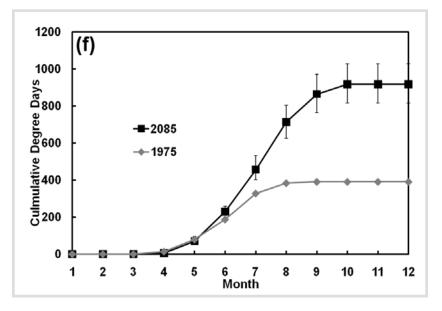
level of damage. It may also cause an earlier onset of insect pests and possibly longer periods of activity.

Discussion

The different results presented here have shown that there are a number of important considerations when predicting the impact of climate change in the future. First, it has been shown that it is important to assess each room individually, as very slight differences can be significant with respect to damage and can amplify potential damage. It has also been shown that it is important to consider seasonal predictions, which could be particularly relevant where preventive conservation measures are in place as some of these may be seasonal according to the opening of the property. It is possible that some preventive conservation measures may need to be adapted to ensure prevention of damage.

The damage function used and its limitations are also vital considerations. Even two similar damage functions can result in different predictions. The two functions to predict dimensional change to wood actually describe two different things. The function presented here predicts a decrease in these damaging events in future, however, the alternate function actually predicts an increase in events. Thus, it is important to consider the type of damage that may be significant to a collection or object and select the most appropriate damage function accordingly. It is imperative to fully understand each of the damage functions being employed.

Perhaps the most paramount consideration is the significance of these predictions. For example, if the number of salt transitions of thenardite/mirabilite increases by 10 transitions in the far future compared to the baseline period, the important point to consider is actually how this is likely to cause damage. It is known that each salt transition is damaging but the magnitude of this damage is not known. Therefore, it is not possible to determine whether this increase in the number of transitions is significant in terms of its potential to cause damage. The same is true for the majority of damage functions: very few actually quantify damage. Attributing significance to future predictions it therefore difficult. The situation

Figure 7. The predicted impact of climate change on degree days in the Cartoon Gallery at Knole. Presented here as the average cumulative total of degree days each month. Error bars represent the interquartile range
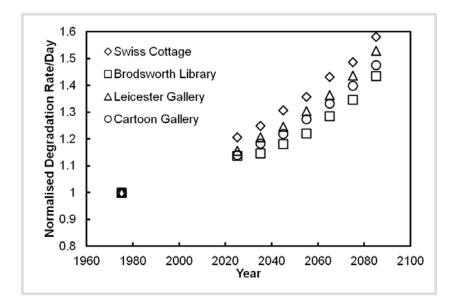
is more clear if there is a specific example, say a wooden sculpture, with no current damage as it would be possible to conclude that any future dimensional change event is likely to be significant. However, examples are rarely so clear-cut. Damage functions that fully describe the damage caused are required, such as the Lipfert function, which describes surface recession of stone. This function explicitly defines the loss of surface in mm/year, a measure which can be easily interpreted to attribute significance. Further work is required to explore the issues surrounding significance; however, an increase in the number of quantitative damage functions would help. A number of the functions described previously are semi-quantitative, and some qualitative, with each step making it more challenging to attribute significance to a predicted change.

Some initial work has attempted to quantify the predictions of the paper damage functions, both between different damage functions and between different locations using the same function. In figure 8, the baseline degradation rate has been normalised to one, and the future rates normalised as a proportion of the baseline rate. While the rates are relative, this process results in the absolute rate increase that is predicted. The relative rates may have no bearing the on actual rate, however the relationship of how these change is the same. Therefore the absolute rate increase is the same as the rate increase between the two relative rates. In figure 8, each location has an increase in rate of approximately 1.5 times by the year 2085. Comparison between the three similar paper damage functions shows that each predicts a 1.5 times increase in chemical degradation of paper by the year 2085.

Conclusions

Predictions of the impact of climate change on historic interiors suggest that indoor temperatures will increase in the future, though less so than outdoors. Changes in relative humidity remain largely unchanged annually, however, seasonal shifts are predicted at Knole. Winter months are predicted to be warmer and slightly more humid, with summer months becoming warmer and less humid. Damage to paper by chemical degradation is predicted to increase in the future due to higher temperatures. Damaging dimensional changes of wood as described by Mecklenburg are predicted to decrease. Salt transitions of thenardite/mirabilite are

largely unaltered, while mould risk is predicted to increase, along with the number of degree days and perhaps, as a result, pest activity.

Careful consideration of all limitations is important when interpreting these results. First, the damage functions must be understood, along with their limitations and second, the uncertainty of future climate models should be taken into account. The building simulation used to predict the indoor climate also has limitations. When using a new damage function with future climate data the function must be fully understood in case any modifications to constants or conversions of reporting units are required.

Predictions of future damage help assess future risks. Even if only an increase or decrease in damage can be predicted, it can be a useful exercise. The predictions allow collection managers to prepare well in advance by introducing preventive conservation measures in sufficient time to prevent any damage increase. This helps to preserve our collections for future generations to enjoy.

References

[1] Lankester, P., and Brimblecombe, P., 'Future thermohygrometric climate within historic houses', Journal of Cultural Heritage 12 (2012) 1–6.

[2] Sabbioni, C., Brimblecombe, P., and Cassar, M., The Atlas of Climate Change Impact on European Cultural Heritage: Scientific Analysis and Management Strategies, Anthem Press, London (2010).

[3] Lankester, P., and Brimblecombe, P., 'The impact of future climate on historic interiors', Science of the Total Environment 417/418 (2012) 248–254.

[4] Lankester, P., The Impact of Climate Change on Historic Interiors, Doctoral thesis, School of Environmental Sciences, University of East Anglia, Norwich (2012) (unpublished).

[5] Intergovernmental Panel on Climate Change (IPCC), 'Summary for policymakers', in Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, ed. M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, C.E. Hanson, Cambridge University Press, Cambridge (2007) 7–22.

[6] Jones, P.D., Kilsby, C. G., Harpham, C., Glenis, V., and Burton, A., UK Climate Projections Science Report: Projections of Future Daily Climate for the UK from the Weather Generator, University of Newcastle, Newcastle (2009).

[7] Intergovernmental Panel on Climate Change, IPCC Special Report Emission Scenarios: Summary for Policymakers, Intergovernmental Panel on Climate Change, London (2000).

[8] Taylor, J., Blades, N., Cassar, M., and Ridley, I., 'Reviewing past environments in a historic house library using building simulation', in Proceedings of ICOM-Committee for Conservation 14th Triennial Meeting, The Hague, ed. I. Verger, James and James, London (2005) 708–715.

[9] Image Permanence Institute, Step-by-Step Workbook: Achieving a Preservation Environment for Collections, Image Permanence Institute, Rochester, New York (2005).

[10] Benavente, D., Brimblecombe, P., and Grossi, C., 'Salt weathering and climate change', in New trends in Analytical, Environmental and Cultural Heritage Chemistry, ed. M. Perla Colombini, L. Tassi, Transworld Research Network, Kerala, India (2008) 277–268.

[11] Hukka, A., and Viitanen, H., 'A mathematical model of mould growth on wooden material', Wood Science and Technology 33 (1999) 475–485.

[12] Isaksson, T., Thelandersson, S., Ekstrand-Tobin, A., and Johansson, P., 'Critical conditions for onset of mould growth under varying climate conditions', Building and Environment 45.7 (2010) 1712–1721.

[13] Jakiela, S., Bratasz, Ł., and Kozłowski, R., 'Numerical modelling of moisture movement and related stress field in lime wood subjected to changing climate conditions', Wood Science and Technology 42 (2008) 21–37.

[14] Luxford, N., Reducing the risk of open display: optimising the preventive conservation of historic silks, Doctoral thesis, University of Southampton, Winchester School of Art (2009) (unpublished).

[15] Mecklenburg, M., Tumosa, C., and Erhardt, D., 'Structural response of painted wood surfaces to changes in ambient relative humidity', in Painted Wood: history and conservation, ed. V. Dorge and F.C. Howlett, the Getty Conservation Institute, Los Angeles (1998) 464–483.

[16] Menart, E., De Bruin, G., and Strlic, M., 'Dose-response functions for historic paper', Polymer Degradation and Stability 96 (2011) 2029–2039.

[17] Michalski, S., 'Quantified risk reduction in the humidity dilemma', APT Bulletin 27.3 (1996) 25–29.

[18] Moon, H.J., and Augenbroe, G., 'Evaluation of hygrothermal models for mold growth avoidance prediction', in Proceedings of the Eighth International IBPSA Conference, 11–14 August 2003, Eindhoven, Netherlands, IBPSA, Eindhoven (2003) 895–902.

[19] Pretzel, B., 'The RIBA project: a climate strategy for paper based archives at the V&A', in 14th Triennial Meeting, The Hague, 12–16 September 2005: Preprints (ICOM Committee for Conservation), ed. I. Verger, James & James/Earthscan, London (2005) 681–688

[20] Reilly, J., Nishimura, D., and Zinn, E., New Tools for Preservation: Assessing Long-Term Environmental Effects on Library and Archives Collections, Commission on Preservation and Access, Washington DC (1995) 42.

[21] Sebera, D., Isoperms. An Environmental Management Tool, Commission on the Preservation and Access, Washington DC (1994).

[22] Zou, X., Uesaka, T., and Gurnagul, N., 'Prediction of paper permanence by accelerated aging I. Kinetic analysis of the aging process', Cellulose 3 (1996) 243–267.

[23] Lipfert, F., 'Atmospheric damage to calcareous stones: comparison and reconciliation of recent experimental findings', Atmospheric Environment 23.2 (1989) 415–429.

[24] Brimblecombe, P., and Grossi, C., 'Millennium-long recession of limestone facades in London', Environmental Geology 56 (2008) 463–471.

[25] Zou, X., Uesaka, T., and Gurnagul, N., 'Prediction of paper permanence by accelerated aging II. Comparison of the predictions with natural aging results', Cellulose 3 (1996) 269–279.

[26] Price, C.A., 'An expert chemical model for determining the environmental conditions needed to prevent salt damage in porous materials', European Commission Research Report 11, (Protection and Conservation of European Cultural Heritage) Archetype, London (2000).

[27] Sedlbauer, K., Krus, M., and Breuer, K., 'Mould growth prediction with a new biohygrothermal method and its application in practice', in Polish Scientific-Technical Conference on Building Physics in Theory and Practice. Materials Conference: Part II, Fraunhofer IBP, Stuttgart (2003) 594–601.

[28] Brimblecombe, P., and Lankester, P., 'Long-term changes in climate and insect damage in historic houses', Studies in Conservation 58.1 (2013) 13–22.

[29] Child, R., 'Insect damage as a function of climate', in Museum Microclimates. Contributions to the Conference in Copenhagen, 19–23 November 2007, ed. T. Padfield, K. Borchersen, National Museum of Denmark, Copenhagen (2007) 57–62.

[30] Pinniger, D., Pest Management in Museums, Archives and Historic Houses, Archetype, London (2001).

[31] Pinniger, D., 'Ten years on – from vodka beetles to risk zones', in Integrated Pest Management for Collections, ed. P. Winsor, D. Pinniger, L. Bacon, B. Child, K. Harris, D. Lauder, J. Phippard, A. Xavier-Rowe, English Heritage, Swindon (2011) 1–9.

Authors

Paul Lankester is an ICON conservation science fellow with the Collections Conservation Team in the National Collections Department of English Heritage. He is currently working on the EU Seventh Framework project MEMORI and is in the process of

finishing his PhD, based around this work.
Email: paul.lankester@english-heritage.org.uk.

Peter Brimblecombe is a professor of atmospheric chemistry at
the School of Environmental Sciences, University of East Anglia;
He is also senior editor of Atmospheric Environment.
Email: p.brimblecombe@uea.ac.uk.

David Thickett is the senior conservation scientist with the
Collections Conservation Team in the National Collections
Department of English Heritage.
Email: david.thickett@english-heritage.org.uk.

Licence

Uncertainties in damage assessments of future indoor climates

Gustaf Leijonhufvud, Erik Kjellström, Tor Broström, Jonathan Ashley-Smith and Dario Camuffo

Abstract

A significant amount of uncertainty is generated in the process of combining projections of future climate, building simulations and damage functions to produce risk maps for historic buildings. The objective of this paper is to identify and qualitatively describe the main uncertainties in the production of such maps. The main sources of uncertainty for each modeling step are identified. It is concluded that the level of uncertainty in risk maps is so high that deterministic approaches have severe limitations, and that further research is needed to assess the levels of uncertainty introduced by each modeling step.

Introduction

Climate change projections and building simulations can be combined to produce scenarios of future indoor climates in historic buildings. Risks to the building or the interiors related to the indoor environment can be assessed with damage functions. The European Climate for Culture project (www.climateforculture.eu) uses this approach and applies it across all of Europe. Instead of using specific, actual buildings, a set of generic buildings are used to transfer outdoor conditions to indoor conditions. In this way it is possible to produce maps of future climate-induced risks to historic buildings and their interiors. The information can be used for climate change impact assessment and for adaption planning of the built cultural heritage. A significant amount of uncertainty is generated in the process of combining projections of future climate, building simulations and damage functions. In this paper we attempt to disaggregate the sources of uncertainty involved in this process.

Climate scenarios describing the future climate are associated with uncertainty, rising from inadequate knowledge of the climate system, imperfections in the numerical climate models and inherent variability in the climate system e.g., [1]. Building simulations and damage functions do not only propagate uncertainties in the climate scenarios but also add new elements of uncertainty.

In a review of probabilistic approaches for climate change impact studies on buildings, Wilde and Tian [2] conclude that although there are strong reasons for such studies to be of probabilistic nature, only a few studies consider uncertainty explicitly. With an unknown, but presumably high level of uncertainty, the results might be practically useless.

The lifespan of building services, changes in use, interventions to the building envelope and other changes in the building and its context play a significant role in long-term prediction of building

performance. These changes may overshadow the impact of climate change and therefore limit the applicability of climate change impact and adaption studies to buildings [2]. Historic buildings, particularly if they are unheated, change less in these respects than standard commercial or residential buildings. Climate change impact and adaption studies therefore seem particularly useful for historic buildings. Generally, cultural heritage management aims at preserving for the far future, which further motivates the study of the impact of climate change.

The approach of simulating the future indoor climate of historic buildings based on regional climate projections has been used in a number of recent studies [3 to 7]. Essentially these studies present a method. The uncertainty in the results is not dealt with, with the exception of Lankester and Brimblecombe [5], who compare three different emission scenarios.

If the propagation of uncertainties is not dealt with there is a risk that data will be used in ways that cannot be supported. If uncertainties are obscured in the final output and described in a deterministic way, decision-makers might come up with adaption strategies that are worse than if no information had existed [8]. The way forward is to address the uncertainties in every step by means of reduction, quantification and communication. A natural starting point for this is to analyze the sources of uncertainty throughout the process.

The objective of this paper is to identify and qualitatively describe the main uncertainties in the production of risk maps based on predicted indoor climates and damage functions.

Uncertainty in risk maps

Much effort has been made to describe and categorize uncertainty in climate change impact and adaption studies e.g., [9, 10], and a consistent and transparent treatment of uncertainty is a prioritized task for the climate change research community e.g., [11]. A common division of the nature of uncertainty is between epistemic and aleatory uncertainty. Epistemic uncertainty comes from a lack of knowledge about a process. It could therefore, in theory, be reduced with a more complete understanding. In practice, it is not always possible to reduce the uncertainty of complex systems, such as the global climate. Aleatory uncertainty, also known as stochastic uncertainty, originates from randomness in nature and the inherent variability in systems. The word aleatory is derived from the Latin word for die, ālea, and the randomness in a closed system such as a pair of dice illustrates this kind of uncertainty. Aleatory uncertainty cannot be reduced; it is a property of the phenomenon being studied. Refsgaard et al. [9] suggest a third kind of uncertainty, ambiguity, which 'results from the presence of multiple ways of understanding or interpreting a system'. To some extent, it is possible to represent both epistemic and aleatory uncertainties with probabilities; this is not the case with ambiguity. Ultimately all kinds of uncertainty stem from a lack of knowledge, and in practice there is no clear division between the different natures of uncertainty discussed here.

The uncertainty cascade of producing risk maps is shown step-by-step in figure 1. The sources of uncertainty in each step will be discussed in the following sections.

Uncertainty in forcing conditions

Changing concentrations of greenhouse gases and aerosols in the atmosphere lead to changing radiative properties of the atmosphere. Changing land use has an impact on surface albedo and surface heat and water fluxes. Changes in the intensity of solar radiation and large volcanic eruptions also have an impact on the climate. Historically, it is clear that anthropogenic forcing agents have dominated over the last centuries and that the result is global warming [12]. The uncertainties are comparatively small concerning the influence of greenhouse gases while they are much larger for the aerosol forcing and also, relatively, for changes in the solar insolation.

For the future, uncertainties in the forcing conditions are related to all of the forcing agents mentioned above. Emission scenarios like the ones suggested in the Special Report on Emissions Scenarios (SRES) [13] from the Intergovernmental Panel on Climate Change, or the more recent Representative Concentration Pathway (RCP) scenarios [14] all represent a large number of different possible pathways into the future and there is no judgement about their likelihood. The SRES scenarios do not include mitigation scenarios, while the RCP scenarios do. Hence, the total uncertainty range is in fact somewhat larger in the newer RCP scenarios. These scenarios pertain only to the anthropogenic forcing agents; changes in solar forcing and volcanic activity are not included.

Uncertainty in climate models

Climate models are highly complex numerical models of the climate system. Due to limitations in computer power, the models cannot resolve all relevant processes and those that are included are often described in a simplified way. Horizontal grid spacing of typically 100–300 km in global models and 10–50 km in regional models implies that phenomena at smaller scales, including for instance clouds and turbulence, cannot be treated explicitly in
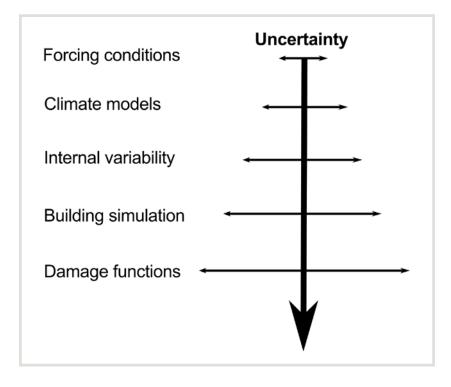

Figure 1. The uncertainty cascade in risk maps

the models. Instead, they need to be described by large-scale parameters that are available in the models. This is referred to as parameterization and is one of the main sources of errors in the climate models. Other uncertainties are related to the fact that we do not know how the climate system works in all its details. Also, all relevant processes may not be included due to computational limitations. For instance, it is only recently that carbon-cycle models have been coupled to climate models with a potentially strong impact on the results [15].

As a result of differences in their formulation, different climate models will project slightly different climates. This is true both in today's climate but also in future and past climates. Differences between models result in both different long-term global average conditions and different regional details in the climate, including extreme conditions. Furthermore, different climate models respond differently to changing forcing conditions.

Uncertainty related to internal variability

The climate is highly variable with variations at many different time scales. Part of the variability is driven by changes in external forcing as described above (e.g., volcanoes, solar irradiation, etc.). But, even if there is no external forcing, the climate will undergo changes. Such variability is referred to as internal variability and it can be associated with different phenomena such as the El-Nino affecting a large part of the Pacific Ocean and surrounding continents e.g.,[16]; or the North-Atlantic Oscillation that has a profound impact on weather and climate in much of Europe [17].

As climate models are designed to simulate the climate system they also include internal climate variability e.g.,[18]. An implication of this is that in simulations when external forcing is changing over time, as in the twentieth and twenty-first centuries, there is a component of internal variability that is part of the overall climate change signal. In some cases such internal variability can amplify the externally driven climate change signal and in some cases it can reduce it.

Climate model integrations often span the time range from c. 1850 to 2100, thus including both historical changes and a future scenario. Starting conditions in 1850 are taken from a control integration with the same model run for several hundred years with constant pre-industrial forcing. These starting conditions will differ from the state of the real climate system at that time. This, in turn, means that the internal variability in the model integration will not be in phase with that of the real climate system. Another experiment with different starting conditions will not be in phase with the first one and the differences between these simulations can be taken as a measure of the uncertainty related to internal variability. Recent findings indicate that the contribution of internal variability may account for at least half of the inter-model spread in projected climate trends during 2005 to 2060 in the multi-model ensemble used in the fourth assessment report by the Intergovernmental Panel on Climate Change [19].

Uncertainty in building simulations

Based on projected future outdoor climate and building properties, the future indoor climate is predicted through building simulation.

The simulation model can be more or less complex, ranging from whole building simulations to linear functions based on a statistical analysis of measurements.

Whole hygrothermal building simulations with large datasets are time-consuming and it is unrealistic to perform them for all locations that can be handled by regional climate models. A shortcut is to use rather simple transfer functions, which give the indoor climate as a function of the outdoor climate.

Lankester and Brimblecombe use a linear function [3, 5]

y = a+bx where

y   indoor temperature or mixing ratio
x   outdoor temperature or mixing ratio
a, b   regression coefficients determined for each month

This transfer function gave a reliable estimate for temperatures but for relative humidity the estimate was less reliable. Bratasz et al. [4] also use the same kind of transfer function but they introduce a time delay for temperature. Nik et al. [20] show that the hygrothermal conditions inside four attics in Sweden are complex non-linear functions of the outdoor conditions, i.e., the variability inside does not follow the outside variability. A linear transfer function would consequently not be able to model this behavior.

The linear fit methodology provides a first-level approximation but there are other methods that better reproduce hysteresis cycles, especially the daily one. In an approach used by Camuffo et al. [21] the forcing factor is an external (daily or seasonal) temperature cycle, and the indoor temperature is obtained by means of a conduction heat transfer based on the heat diffusion equation in Cartesian coordinates. The method results in a time-dependent equation that expresses the heat flux in terms of the current temperature and the past histories of both temperature and heat flux.

Huijbregts et al. [6] use the building simulation model HAMBase to calculate the indoor climate from the predicted outdoor climate. The model gives a good agreement with measured values for temperature. For relative humidity the agreement is better than for the simple transfer functions, but there is still a significant error.

To produce risk maps it is advantageous to use generic building types for the simulation of indoor climates. One generic building type is supposed to represent a category of actual buildings, an approach previously used by Crawley [22]. Although this methodology seems to have potential, it has not been widely used and the common approach is to use selected case study buildings [2]. Essentially, there are three sources of uncertainty in building simulation, irrespective of the complexity of the used model [23]:

1. Specification uncertainty due to discrepancies between the building and the model. In general, this uncertainty is higher for historic buildings as the composition of the building envelope might not be known and the physical properties of old building materials vary more within and between buildings. The use of generic building types for simulation introduces a high level of specification uncertainty. The level of this uncertainty is a

matter of how well the types represent actual buildings. It can be reduced with the use of a larger set of generic buildings, thereby better representing groups of actual buildings.

2. Modeling uncertainty due to deficiencies in the model itself. This includes uncertainty of microclimates in the building. The level of modeling uncertainty with transfer functions is higher than for whole building simulations. Nik et al. [20] studied the effect of climate change on typical Swedish attics. They showed that the difference between three different emission scenarios was insignificant for the risk of mould growth. Interestingly, this could be explained with the higher shortwave radiation intensity of the low emission scenario that showed less cloud than the other scenarios. With the use of a simpler model, omitting solar radiation, this effect would have been obscured.

3. Scenario uncertainty due to uncertainties about external conditions, such as climate conditions and changes to the building or the use of the building. Included in this category is the conversion of data from climate projections to the temporal and spatial resolution needed for building simulation, usually hourly values for a given location. Climate model projections deliver values representative of an area, which have to be downscaled to a specific location. This additional downscaling adds further uncertainty, which can be high, particularly for locations with complex topography. In a long-term perspective, changes can be expected in the use of a building, in climate-control systems and in the building envelope. Any model validated for the present conditions will thus be more or less valid for the future.

In summary, it is clear that the use of generic buildings and transfer functions, as opposed to real buildings and whole building simulations, introduces more uncertainty. Despite the added uncertainty it seems as if this approach is the most viable option for the production of risk maps. By comparing case-study buildings with generic buildings, as well as transfer functions with whole building simulations, it would be possible to assess the difference.

Uncertainty in damage functions

In this paper we use the term damage function to describe a quantitative expression of cause and effect relationships between environmental factors and material change. We suggest that uncertainties in damage functions originate from three fundamental sources:

1. Input uncertainty. This is uncertainty of the properties of objects as well as uncertainty of input data. Many damage functions are based on the behaviour of one single material and are not representative of the wide variety of forms in which different materials are found in heritage objects. For example, the material 'paper' could be old, new, acid, alkaline, have high or low lignin content and be in the form of a single sheet or a book. All these factors would affect the response, but they may not be included in the damage function. The uncertainty of input data arises from uncertainties in measured or predicted data. One problem is the formation of microclimates, i.e., the climate might differ significantly within a room and therefore not be representative for the deterioration mechanism of concern.

Another problem is that in hygroscopic materials several deterioration mechanisms e.g., swelling-shrinking, hydrolysis, corrosion, mould growth, hydration and mineral transformation, depend on moisture content. However, as moisture content is difficult to measure, relative humidity is often used as a proxy in damage functions. In reality the relationship between moisture content and relative humidity is dynamic, characterized by cycles and fluctuations, and the temperature of an object is not the same as the air temperature. In addition, heat diffuses faster than moisture in hygroscopic materials, causing internal unbalances under dynamic conditions.

2. Deficiencies of the function itself and the natural variability of the deterioration process. There might be synergistic effects that are not included in the function. This uncertainty is rarely quantified but it should be possible to produce probabilistic damage functions in many cases.

3. The interpretation of the output, i.e., the predicted material change. This is a significant source of uncertainty due to ambiguity. Most damage functions will only predict a relative change. If generic buildings are used this is not necessarily problematic, as there are no actual objects for which absolute damage could be predicted. Furthermore, it is uncertain to what extent a material change will be interpreted as damage; it is by nature subjective.

The significance of uncertainties in the predicted indoor climate resulting from climate projections and building simulation will vary for different types of cause-effect relationships, as these are not equally sensitive to variability or extreme climatic events.

The type of relationship that is most straightforward to model with a damage function is one where the effect can be expressed as the product of the intensity of a physical variable and its duration, which is known as a dose-response relationship. One example is colour fading which depends on the product of light intensity and time. Most deterioration mechanisms are not strict dose-response relationships although there may be cumulative effects over time. Some of these can be described with relatively simple functions depending on one or more variables. One example is the chemical deterioration of paper due to cellulose hydrolysis, which can be approximately predicted by combinations of relative humidity levels and temperature resulting in the same relative rate of deterioration.

When the cause-effect relationship is neither a dose-response, nor a simple function of one or more physical variables, the problem is more complex. Furthermore, the functional variables might be mixed and involve synergisms. In these cases it becomes more difficult to mathematically describe the relationship with a damage function.

An example of one such complex cause-effect relationship is mould germination and growth. Most models use a combination of relative humidity, temperature and time for prediction e.g., [24]. The germination of mould is a threshold phenomenon and therefore sensitive to extreme conditions for a limited period of time. Mould growth, on the other hand, is cumulative. Although it is not well established how variability in temperature and relative

humidity affect mould, it has been shown that fluctuating relative humidity decreases growth of mould also in relation to cumulative time at relative humidity levels that permit growth at constant moisture conditions [25].

Given the fundamental differences in time-dependency and cumulative effects between different damage functions it seems plausible that uncertainties in predicted indoor climates will play different roles for different types of functions. For example, uncertainty about variability and extreme events will be of less concern for cellulose hydrolysis than mould germination and growth.

Further research is needed to establish the sensitivity of damage functions in relation to upstream uncertainties. With the current state of knowledge this is more or less guesswork.

This overview has pointed at possible sources of uncertainty in damage functions but not discussed their magnitude. Although the sources are many, it is not the case that most damage functions are saturated with uncertainty. Many damage functions which are derived from laboratory work perform well when tested on heritage objects in a museum environment.

Discussion

As shown in the previous section, there are significant uncertainties introduced at each modeling step in the production of risk maps. The sources of uncertainty and their dominating nature are summarized in table 1. The relative levels of these uncertainties and how they propagate through the process to produce risk maps are to a large extent unknown. Furthermore, little is known about how important this gap in knowledge is for the final assessment of risk maps, both in the case of estimated impact and for adaption planning. A common definition of risk is probability times consequence. Actually the term risk map is misleading for the type of map discussed in this paper, if the aspect of probability or likelihood is excluded.

An intuitive direction of research to bridge this gap would be to quantify uncertainties for the whole chain. In this vein, Tian and Wilde [26] outline the methodological steps needed for a

Table 1. The major sources of uncertainty for each modeling step in the production of risk maps and the dominating nature of uncertainty for each source. Adapted from [9]

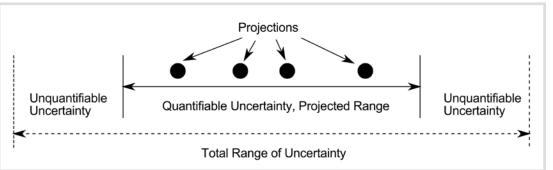| Modeling step	Major source of uncertainty	Dominating nature of uncertainty
Forcing conditions	Socio-economic pathways	Ambiguity, epistemic
Climate models	Model deficiencies	Epistemic
Internal variability	Randomness in nature	Aleatory, epistemic
Building simulations	Specification	Epistemic
	Model	Epistemic
	Scenario	Ambiguity, epistemic
Damage functions	Input	Epistemic
	Deficiencies of the function	Epistemic, aleatory
	Interpretation	Ambiguity

probabilistic treatment of building performance in relation to climate projections, based on global sensitivity analysis. This methodology could be extended to include damage functions. As mentioned above, there is a need for sensitivity analysis to analyze how damage functions are affected by upstream uncertainties from climate projections and building simulation.

The use of building simulation and damage functions as an extension to climate projections is a top-down approach where the output is a predicted value (with the possibility to add a probability range). There is a possibility to use a bottom-up process instead, where intolerable risk is expressed as a combination of thresholds for different climatic parameters. The likelihood of exceeding these thresholds would then be analyzed and used for risk assessment [27].

However, it is only possible to quantify a limited part of the whole uncertainty range, as shown in figure 2. In effect, there will always be a large amount of residual uncertainty left, despite the best efforts of research. Whereas aleatory and epistemic uncertainty can be quantified to some extent, ambiguity is not amenable to quantification at all. From the summary in table 1 it is evident that there are important sources of uncertainty in risk maps, which are by nature ambiguous. As pointed out by Dessai and Hulme [28], uncertainties about future climate change will always be subjective and conditional, and further research might actually increase uncertainty as new unknown uncertainties are discovered. This is a strong argument that adaption planning should not rely on increasingly precise predictions, i.e., reduced uncertainty. Instead, adaption measures could be implemented that are robust for a range of possible future climates and states of the world [29, 30].

All risk management decisions, and consequently all adaption planning decisions, do not require the same level of treatment of uncertainty; sometimes best-estimates or worst cases are sufficient for decision-making [31]. The use of worst cases is widely used for decision-making in preventive conservation, and many damage functions are based on this concept. Even though worst cases are appealing because of the intuitive ease with which they seem to inform decision-making, they are most useful in the case of a negative result, i.e., that climate change will not matter for the object under consideration. However, this result will be obvious if a wider range of probability distributions are considered. Furthermore, it is not an easy task to define the worst case given the many modeling steps needed to produce risk maps. For each modeling step some moderation of the worst case is needed in order to ignore extremely unlikely outcomes. This moderation results in a quasi-worst case that represents a truncation of the probability distribution. Both quasi-worst cases and best-estimates can be problematic when used for policy decisions [31, 32]. The limited resources available for cultural heritage make trade-offs between risks a necessity, and such trade-offs are best done in a risk management framework where the overall magnitudes of different risks are compared.

A final question is how risk maps should be designed and selected, given the high level of uncertainty involved. To answer this question, there is a need to define who the likely end-users are. If politicians are the intended audience it may be necessary to conceive a few generic risk combinations that summarize changes due to climate change. Conservation students would want as many

Figure 2. The relationship between damage projections, a projected range and a total range of uncertainty. Adapted from [10]

maps devoted to hazard-material interaction as possible. The stakeholder with administrative responsibility for a given site or group of sites would probably not need the generalized output of a map but require specific data about that one location, as maps can only give generalized views over large geographic areas.

Despite the many challenges ahead, it should be the aim of research to assess the relative importance of different uncertainties and to communicate uncertainties effectively to decision-makers [33]. How uncertainties should be communicated in risk maps is a further topic of study. Effective communication of uncertainty is a challenging task, even when full probability distributions are known [34].

Conclusion

The objective of this paper was to identify and qualitatively describe the main uncertainties in the production of risk maps based on predicted indoor climates and damage functions. The main sources of uncertainty in each step of the modeling process were disaggregated and discussed. The key findings are that:

- the level of uncertainty in risk maps is so high that deterministic approaches have severe limitations. As an alternative, uncertainty could be addressed by the use of a probabilistic approach. However, there will always be a significant amount of residual uncertainty that cannot be quantified.
- each modeling step introduce significant uncertainty, and the relative levels of these uncertainties need to be further studied.

Although the final level of uncertainty in risk maps will be high regardless of whether a deterministic or a probabilistic approach is used, risk maps based on state-of-the-art scientific knowledge are valuable as indicators of future risks to cultural heritage and they will play an important role in informing mitigation and adaption planning at different levels.

Acknowledgements

References

[1] Hawkins, E., and Sutton, R., 'The potential to narrow uncertainty in regional climate predictions', Bulletin of the American Meteorological Society 90.8 (2009) 1095–1107.

[2] Wilde, P. de, and Tian, W., 'Towards probabilistic performance metrics for climate change impact studies', Energy and Buildings 43.11 (2011) 3013–3018.

[3] Lankester, P., and Brimblecombe, P., 'Future thermohygrometric climate within historic houses', Journal of Cultural Heritage 13.1 (2012) 1–6.

[4] Bratasz, Ł., Harris, I., Lasyk, Ł., Łukomski, M., and Kozłowski, R., 'Future climate-induced pressures on painted wood', Journal of Cultural Heritage 13.4 (2012) 365–370.

[5] Lankester, P., and Brimblecombe, P., 'The impact of future climate on historic interiors', Science of The Total Environment 417–418 (2012) 248–254.

[6] Huijbregts, Z., Kramer, R.P., Martens, M.H.J., Schijndel, A.W.M. van, and Schellen, H.L., 'A proposed method to assess the damage risk of future climate change to museum objects in historic buildings: Implications of a Changing Climate for Buildings', Building and Environment 55.0 (2012) 43–56.

[7] Brimblecombe, P., and Lankester, P., 'Long-term changes in climate and insect damage in historic houses', Studies in Conservation 58.1 (2012) 13–22.

[8] Preston, B., Yuen, E., and Westaway, R., 'Putting vulnerability to climate change on the map: a review of approaches, benefits, and risks', Sustainability Science 6.2 (2011) 177–202.

[9] Refsgaard, J., Arnbjerg-Nielsen, K., Drews, M., Halsnæs, K., Jeppesen, E., Madsen, H., Markandya, A., Olesen, J., Porter, J., and Christensen, J., 'The role of uncertainty in climate change adaptation strategies - A Danish water management example', Mitigation and Adaptation Strategies for Global Change 18.3 (2013) 337–359.

[10] Jones, R.N., 'Managing uncertainty in climate change projections – issues for impact assessment', Climatic Change 45.3 (2000) 403–419.

[11] Mastrandrea, M.D., Mach, K.J., Plattner, G.K., Edenhofer, O., Stocker, T.F., Field, C.B., Ebi, K.L., and Matschoss, P.R., 'The IPCC AR5 guidance note on consistent treatment of uncertainties: A common approach across the working groups', Climatic Change 108.4 (2011) 675–691.

[12] IPCC, The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, ed., S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, H.L. Miller, Cambridge University Press, Cambridge and New York (2007) 235–337.

[13] Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grubler, A., Jung, T., and Kram, T., Special Report on Emissions Scenarios: a special report of Working Group III of the Intergovernmental Panel on Climate Change, Intergovernmental Panel on Climate Change (2000).

[14] Moss, R., Edmonds, J., Hibbard, K., Manning, M., Rose, S., van Vuuren, D., Carter, T., Emori, S., Kainuma, M., and Kram, T., 'The next generation of scenarios for climate change research and assessment', Nature 463.7282 (2010) 747–756.

[15] Friedlingstein, P., Cox, P., Betts, R., Bopp, L., Bloh, W. von, Brovkin, V., Cadule, P., Doney, S., Eby, M., and Fung, I., 'Climate-carbon cycle feedback analysis: Results from the C4MIP model intercomparison', Journal of Climate 19.14 (2006) 3337–3353.

[16] Trenberth, K., 'The definition of el nino', Bulletin of the American Meteorological Society 78.12 (1997) 2771–2777.

[17] Hurrell, J., 'Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation', Science-AAAS-Weekly Paper Edition 269.5224 (1995) 676–678.

[18] Jungclaus, J.H., Lorenz, S.J., Timmreck, C., Reick, C.H., Brovkin, V., Six, K., Segschneider, J., Giorgetta, M.A., Crowley, T.J., and Pongratz, J., Climate and carbon-cycle variability over the last millennium, Climate of the Past 6.5 (2010) 723–737.

[19] Deser, C., Phillips, A., Bourdette, V., and Teng, H., 'Uncertainty in climate change projections: the role of internal variability', Climate Dynamics 38.3–4 (2012) 527–546.

[20] Nik, V.M., Sasic Kalagasidis, A., and Kjellström, E., 'Assessment of hygrothermal performance and mould growth risk in ventilated attics in respect to possible climate changes in Sweden: Implications of a Changing Climate for Buildings', Building and Environment 55.0 (2012) 96–109.

[21] Camuffo, D., Bertolin, C., Bonazzi, A. Campana, F., and Merlo, C., 'Past, present and future effects of climate change on a wooden inlay bookcase cabinet: a new methodology inspired to the novel European Standard EN 15757: 2010', Journal of Cultural Heritage (in press).

[22] Crawley, D.B., 'Estimating the impacts of climate change and urbanization on building performance', Journal of Building Performance Simulation 1.2 (2008) 91–115.

[23] Wit, S. de, 'Uncertainty in building simulation', in Advanced building simulation, ed. A. Malkawi, G. Augenbroe, Spon, London, New York (2003), 25–59.

[24] Isaksson, T., Thelandersson, S., Ekstrand-Tobin, A., and Johansson, P., 'Critical conditions for onset of mould growth under varying climate conditions', Building and Environment 45.7 (2010) 1712–1721.

[25] Viitanen, H., and Bjurman, J., 'Mould growth on wood under fluctuating humidity conditions', Material und Organismen 29.1 (1994) 27–46.

[26] Tian, W., and Wilde, P. de, 'Uncertainty and sensitivity analysis of building performance using probabilistic climate projections: A UK case study', Automation in Construction 20.8 (2011) 1096–1109.

[27] Jones, R.N., 'An Environmental Risk Assessment/Management Framework for Climate Change Impact Assessments', Natural Hazards 23.2 (2001) 197–230.

[28] Dessai, S., and Hulme, M., 'Does climate adaptation policy need probabilities?', Climate Policy 4.2 (2004) 107–128.

[29] Dessai, S., Hulme, M., Lempert, R., and Pielke Jr, R., 'Climate prediction: a limit to adaptation', in Adapting to Climate Change: Thresholds, values, governance, ed. W.N. Adger, I. Lorenzoni, K.L. O'Brien, Cambridge University Press, Cambridge, New York (2009), 64–78.

[30] Weaver, C.P., Lempert, R.J., Brown, C., Hall, J.A., Revell, D., and Sarewitz, D., 'Improving the contribution of climate model information to decision making: the value and demands of robust decision frameworks', Wiley Interdisciplinary Reviews: Climate Change 4.1 (2013) 39–60.

[31] Paté-Cornell, M., 'Uncertainties in risk analysis: Six levels of treatment', Reliability Engineering & System Safety 54.2 (1996) 95–111.

[32] Webster, M., Sokolov, A., Reilly, J., Forest, C., Paltsev, S., Schlosser, A., Wang, C., Kicklighter, D., Sarofim, M., Melillo, J., Prinn, R., and Jacoby, H., 'Analysis of climate policy targets under uncertainty', Climatic Change 112.3–4 (2012) 569–583.

[33] Foley, A.M., 'Uncertainty in regional climate modelling: A review', Progress in Physical Geography 34.5 (2010) 647–670.

[34] Spiegelhalter, D., Pearson, M., and Short, I., 'Visualizing uncertainty about the future', Science 333.6048 (2011) 1393–1400.

Authors

Gustaf Leijonhufvud is a PhD student in conservation at Gotland University and University of Gothenburg. His research is about energy efficiency and preventive conservation through environmental control. Email: gustafl@hgo.se

Erik Kjellström is an associate professor and climate researcher at Rossby Centre, Swedish Meteorological and Hydrological Institute, Norrköping. His current research involves evaluation of results from the regional climate model at the Rossby Centre. Assessing uncertainties in climate change projections and providing ensemble based probabilistic scenarios is another field of interest. Email: erik.kjellstrom@smhi.se

Tor Broström is a professor in building conservation and Head of the Center for Energy Efficiency in Historic buildings at Gotland University. He is also coordinator of the Swedish national research program on energy efficiency in historic buildings. His research is focused on energy efficiency and indoor climate control in buildings with culture heritage values. Email: tor.brostrom@hgo.se

Jonathan Ashley-Smith is an independent teacher and consultant. He trained as a chemist to post-doctoral level and was formally Head of Conservation at the Victoria and Albert Museum, London (1977 to 2002). He is currently leader of the risk and damage

assessment work package within the European project Climate for Culture. Email: jashleysmith@btinternet.com

Dario Camuffo is Research Director at the Institute of Atmospheric Sciences and Climate (ISAC) within the Italian National Research Council (CNR), Padua. His main scientific interests are: atmospheric sciences, climate change and natural hazards, microclimate and conservation of cultural heritage. He has led many Italian research projects and some fifteen EU-funded projects on these subjects. Email: d.camuffo@isac.cnr.it

The influence of the museum environment in controlling insect pests

Robert Child

Abstract

Insect pests that attack museum collections are small and have a very large body surface area compared with their volume. This, combined with their habit of inhabiting microclimates within the general environment, make them very responsive to local temperature, humidity and other climatic factors. Small variations in these factors, often unnoticeable to the human occupants, can radically affect their behaviour such as their ability to move, mate and fly. In the longer term, climatic conditions affect the length of life cycles, the spread of the habitat and other factors that can turn a minor attack into a major infestation. Through a better understanding of the insect pest species involved and their lifestyles, better preventive and control measures can be introduced.

Insecticides and the Law

With the introduction in the United Kingdom of the Control of Pesticide Regulations Act 1986 (as amended 1997) [1], the country saw most of the very effective, but hazardous, pesticides banned. Insecticides such as mercuric chloride, DDT, pentachlorophenol and arsenic, which had traditionally been used on museum specimens for decades, were now no longer available. Although their legacy remains! It was no longer legal to treat large quantities of infested material with effective fumigants such as ethylene oxide and hydrogen cyanide. More recently, the Montreal Agreement [2] has restricted the use of methyl bromide as a fumigant owing to its ozone-depleting properties. The European Union's Biocide Directive 1998 [3] is regulating all pesticides in an attempt to harmonise pest control measures in the 27 member countries, and many that are not registered are being banned. Again, many traditional pesticides and repellents such as naphthalene and citronella are now no longer available. Worryingly, the Biocides Directive covers 'active substances intended to destroy, deter, render harmless, prevent the action of, or otherwise exert a controlling effect on any harmful organism by chemical or biological means'. As the testing for recognition and registering of such a substance is expensive (up to 250,000 €) many companies are not doing so and therefore the material is de-registered and so banned in the EU. Substances under investigation include pheromone attractants, repellents such as lavender and cedar wood and generic insecticides such as borax.

In the UK many other legal issues affect the use of chemical and biological insecticides such as the Control of Substances Hazardous to Health 2002 regulations, Health, Safety and Welfare 1992 regulations and many others. In the conservation profession, the British Standards Institute has recently issued two documents which have an effect on insect pest control, namely PD5454:2012 Guide for the Storage and Exhibition of Archival Material [4] and

PAS 198:2012 Specification for Managing Environmental Conditions for Cultural Collections [5]. Other countries have similar legislation and guidelines.

Integrated pest management (IPM) is increasingly concentrating on non-chemical means for monitoring and control of insect pests in historic buildings and heritage collections. Exclusion of pests is an obvious starting point, but with museums, galleries and historic buildings being open public spaces with people and material constantly moving in and out, total exclusion of insects is impossible. Regular monitoring for the presence of insects is vital and necessary, but this is no more that a monitoring exercise, not a control treatment. Even enhanced trapping methods using attractants such as sex pheromones will not control an infestation. An understanding of the specific environmental requirements of insects will allow the museum to provide conditions inimicable to insect development and therefore minimise or prevent their establishment in the museum structure of collections.

Insects: conditions for life
The effect of temperature

The majority of insect pests affecting historic collections exist happily at temperatures between 15 to 30 °C. All activity stops at temperatures below 5 °C [6] but many insects, such as clothes moth can survive at these temperatures. In nature, many insects survive over winter by developing glycol based anti-freeze mechanisms and can even survive freezing.

At temperatures above 15 °C insects tend to become increasingly active and the following general observations can be made:

At below 15 °C insects are sluggish, cannot fly and can only move in a limited area. Mating is possible but egg-laying is localised. Larvae grow slowly so commensurate damage to objects is limited. Time spent as a pupa is extended so the insect has an extended life cycle. Some smaller moths can attempt to fly by vibrating their wings to warm up.

At above 20 °C insects increasingly have the ability to fly, therefore spreading infestations wider and higher. House longhorn beetle (Hylotropes bajalus) and other woodborers can only fly at temperatures above 25 °C [7]. Higher temperatures increase the insect's metabolic rate, so that its life cycle is dramatically shortened. Webbing clothes moth has a natural annual life cycle outside. Indoors in centrally heated buildings, it may have two or three life cycles in a year. This is because the eggs hatch more quickly, the larvae can eat faster, the pupal stage is shortened and the adults can fly and mate more quickly.

At above 30 °C many insect pests become uncomfortable and start to die [8]. Some can survive short periods of high temperatures by evaporating their body moisture, but over a longer period will desiccate and die. Furniture beetle (Anobium punctatum) cannot survive, as essential yeasts consumed by the larvae are killed at temperatures above 26°C.

High temperatures. It is generally accepted that insects at all life stages will be killed at temperatures above 52 °C when exposed for longer than one hour [9]. Allowance has to be made for the

insulation effect of the material the insect is inhabiting to allow the heat to penetrate through it.

Insects moving north

With a combination of global warming, warmer buildings and high comfort temperatures, many insect pests that could formerly not survive in the colder northern climates, now can. The northward trend of subterranean termites is well documented with a long-term trend up through France and in the USA, and incidental established infestations in the UK from imported infested timber [5]. In the UK the surge northwards of the Guernsey carpet beetle is instructive. The chronology is this [7]:

• Guernsey carpet beetle, Anthrenus sarnicus, first recorded in Guernsey, Channel Island, 1961
• Recorded in London, UK, 1963
• Found in the British Museum (Natural History) in 1973
• Recorded in Liverpool in 1982
• Reported in Royal Museum of Scotland, Edinburgh in 1991 [10].

Similar observations of other pest insects have been reported in many countries. Recently, another carpet beetle species, Attagenus smirnovii, which originates from Kenya has become well established in the UK and other countries in Europe [9]. Other insect pests making their debut in cooler countries include Reesa vespula, which is becoming a major pest owing to it being parthenogenic (that is no males are needed for breeding). Countries such as Scotland, previously free of some pests such as death watch beetle (Xestobium rufovillosum), now have them.

The explanation is two-fold. The first is warmer internal and external temperatures from natural climatic and central heating causes. Secondly, many insects have the ability to acclimatise to different environmental conditions. The cockroach is known to be able to exist and thrive in both very cold conditions or extremely hot ones, but cannot survive if transferred from one to the other. Warmer conditions also increase insect development with faster breeding, a greater ability to move and fly, all of which contribute to the spread of insect pests.

The effect of humidity

Insects, like all animals, are primarily composed of water. Having such a large body surface area compared with their volume, they are very vulnerable to drying out, which causes death. This is prevented by the insect having a waterproof outer waxy layer covering the epicuticle, and by limiting water loss by evaporation through the breathing spiracles and anus [11].

It is estimated that most insects have an internal moisture content equivalent to a surrounding relative humidity (RH) of 99.5 % [11]. Insects can obtain their moisture requirements in a number of ways. Some adult beetles such as the Australian spider beetle (Ptinus tectus), and some cockroaches, need liquid water. These adults can often be found near water sources including pot plants, water leaks, etc. Some, such as the biscuit beetle (Stegobium panaceum) and the webbing clothes moth (Tineola bisselliella) have larvae that can metabolise water from their food. This explains their ability to colonise material of low moisture content

(MC) and surrounding relative humidity. Webbing clothes moth can happily thrive in relative humidities (RHs) as low as 30 %, and this is a reason for its success as a major museum and domestic pest.

However, most insects get their moisture from the food the larvae eat or directly from high localised RHs. Many insects such as the woodborers, furniture beetle, death watch beetle and house longhorn beetle need moisture content in the wood of above 15 %. This corresponds to a surrounding RH of above 65 %. Below this level, eggs will desiccate and die and larvae cannot exist. Other insects such as silverfish and booklice feed on microscopic moulds growing on cellulosic material. These moulds need localised RHs of above 80 %, so lowering the RH to below this limit kills both the mould and the insects [12]. In general, keeping RH levels below 65 % inhibits much of insect development and is in keeping with other preventive conservation measures.

The effect of light

Many pests have two different approaches to light and ultra-violet radiation (UV). At certain times of their life cycle they are attracted to light and at other times they seek darkness. In general, insects look for light to find a mate and then the females look for quiet, dark, food-attractive areas to lay their eggs. Some will seek dark indoor areas to hibernate (such as cluster flies and harlequin ladybirds) and be a pest when they try to return to the outside with the warmth of spring.

Carpet beetle adults (Anthrenus and Attagenus spp) feed on nectar and mate outside on certain flower specie (such as Spirae). They are therefore found on windowsills in early summer or can be captured on light traps in dark stores. Death watch beetle adults are thought to be attracted to UV light and can be caught in great numbers on UV electrocutor traps so long as the temperature is high enough for them to fly [7].

The effect of insecticidal treatments

Most insecticidal treatments are more effective at higher temperatures. Monitoring with blunder or pheromone traps is most effective at temperatures above 20 °C when the adults are active and flying. Tests with webbing clothes moth pheromone traps found the optimum to be placing the traps at 1.5 metres high in temperatures around 25 °C [13].

Some insecticides, including some of the chlorinated hydrocarbons, such as DDT and Lindane (γHCH), are more effective at killing at lower temperatures (below 20 °C) but suffer the disadvantage that the insects, being less active, may not come into contact with them. Most insecticides are contact insecticides so rely on the insect coming into contact with them. Higher temperatures mean greater mobility and thus more contact and efficacy of killing.

Insecticides which rely on high levels of metabolic activity are more effective at high temperatures. So fumigants, such as carbon dioxide and sulfuryl fluoride and anoxic measures using nitrogen, are often ineffective under 25 °C, and may need several weeks of treatment.

Altering the environment to deter insect pest development

In general by lowering temperatures and relative humidities insect development can be slowed. Storage areas only intermittently visited by people can be allowed to cool naturally in winter without the need for human comfort heating. By allowing the ambient temperature to drop to a minimum of 5 to 10 °C considerable energy savings can be achieved and satisfactory relative humidities maintained. Lower temperatures are inadvisable owing to the possibility of localised condensation.

Temperatures maintained below 15 °C for most of the year will effectively prevent most insect development and, when it occurs, limit its growth both by extending the life cycle and restricting movement.

Relative humidities of below 65 % will generate moisture contents in organic materials below 15 %, provided no other water source is present. Localised high humidities and related moisture content can exist where there is damp from leaking pipes, water penetration through walls and floors or by being adjacent to cold surfaces. In the northern hemisphere internal cold north-facing walls, which receive no solar warming, are classic sites for finding mould growth and insect pests.

Low relative humidities and moisture contents will restrict pests of cellulosic material, such as the woodborers, silverfish and booklice. However the keratinous feeders, including clothes moths and carpet beetle, can survive in lower humidities down to 30 %, but are slow to develop. Optimum growth for the webbing clothes moth (Tineola bisselliella) occurs at temperatures of 25 to 30 °C and a RH of 70 %.

Use of light and UV traps at appropriate times in an insect's life cycle (usually after adult moth or beetle emergence from the pupal stage) can be valuable as both a monitoring, and to some degree, a control measure.

Conclusion

Preventive conservation is designed to minimise deterioration of all museum materials, both inorganic and organic. Low temperatures slow down all chemical reactions (the Arrhenius effect). Most deteriorative reactions involve water, including metal corrosion and biological growth. Therefore by strategically lowering relative humidities and associated moisture contents, deterioration mechanisms can be slowed or even stopped. Integrated pest management by controlling the environment around insects to limit their growth is an integral part of a preventive conservation programme.

References

[1] Control of Pesticides Regulations 1986 (as amended 1997), www.legislation.gov.uk (accessed 17 September 2012).

[2] Montreal Agreement, www.en.wikipedia.org (accessed 17 September 2012).

[3] The Biocidal Products Regulations 2001, www.legislation.gov.uk (accessed 17 September 2012).

[4] PD 5454:2012, Guide for the Storage and Exhibition of Archival Material, BSI Standards Limited (2012).

[5] PAS 198:2012, Specification for Managing Environmental Conditions for Cultural Collections, BSI Standards Limited (2012).

[6] Busvine, J.R., Insects and Hygiene, Chapman and Hall, London (1980).

[7] Ridout, B., Timber Decay in Buildings, E. and F.N, Spon, London (2000).

[8] Strang, T.J.K., 'A review of published temperatures for control of pest insects in museums', Collection Forum 8.2 (1992) 41–67.

[9] Stengaard Hansen, L., Åkerlund, M., Grøntoft, T., Ryhl-Svendsen, M., Schmidt, A.L., Bergh, J.E., and Jensen, K.M.V., 'The brown carpet beetle. Attagenus smirnovii: How will climate change affect its future pest status?', in Integrated Pest Management for Collections. Proceedings of 2011: A Pest odyssey, 10 years later, ed. P. Winsor, English Heritage, Swindon (2011) 55–60.

[10] Shaw, M.R., 'New threats from museum beetles', SSCR Journal 2.5 (1991) 15–16.

[11] Unwin, D.M., and Corbet, S.A., Insects and Plants and Microclimates: Naturalists' Handbook 15, Richmond Publishing, Slough (1991).

[12] Findlay, W.P.K., The Preservation of Timber, A. and C. Black, London (1962).

[13] Child, R.E., 'Insect damage as a function of climate', Museum Microclimates: Contributions to the conference in Copenhagen, 19–23 November 2007, ed. T. Padfield, K. Borchersen, National Museum of Denmark, Copenhagen (2007) 57–62.

Author

Robert Child was formerly Head of Conservation at the National Museum of Wales, UK, and is now a consultant in preventive conservation specialising in environmental and biological control. As such, he is the Advisor to the National Trust on insect pests. Email: bob.child@ntlworld.com

Licence

Inverse modeling of climate responses of monumental buildings

Rick Kramer, Jos van Schijndel and Henk Schellen

Abstract

The indoor climate conditions of monumental buildings are very important for the conservation of their collections and the building themselves. Simplified models capable of simulating temperature and humidity are needed, which may be applied to real situations. In this paper we research state space models as a methodology for the inverse modeling of climate responses of unheated monumental buildings. This approach proves very promising for obtaining physical models and the parameters of indoor climate responses. Furthermore, state space models can be simulated very efficiently: to simulate 100 years of hourly data takes less than a second on an ordinary computer.

Introduction

The effects of climate change on ecosystems and on the global economy have been researched intensively over the past decades but almost nothing is known about the influence on our cultural heritage. Although historical monuments are exposed to extensive stress from stampedes of visitors, there are many other factors involved in the deterioration of World Heritage Sites. The impacts of climate change are a long-term and substantial menace to the sites. Many monumental buildings are used as museums or stores for paintings, books and artefacts. The indoor climate conditions of monumental buildings are very important for the conservation of these objects [1]. The influence of the changing external environment on the indoor climate of monumental buildings is unknown. Because of this lack of knowledge it is impossible to prepare adequately for the future by anticipating changes and adapting arrangements [2]. This places buildings and collections at risk. Furthermore, the worldwide energy problem is also a significant factor. Due to ancient building techniques historic buildings are often poorly insulated, meaning energy consumption is high.

Current methods of researching the effects of climate change on monumental buildings and their collections mainly consist of performing computer simulations and analysing the results. Three problems can be identified with these methods: (i) due to the long time periods being considered (100 years with time steps of one hour), combined with the detail of the physical models, the simulation run-times are long; (ii) the detailed modeling of the buildings requires considerable effort as they are old and protected, blueprints may not be readily available and destructive methods to obtain building material properties are rarely countenanced; (iii) the modeling approaches used do not facilitate simple characterisations of the buildings nor their energy efficiency.

Simplified models capable of simulating both temperature and humidity are needed, which may be applied to real situations. The objective of the current research is the successful application of inverse modeling on a simplified thermal and hygric building model in order to determine parameters with physical meaning. The simplified model should be capable of predicting indoor temperature and humidity and of characterising the building and its energy performance.

The paper is organised as follows: we begin with a literature study on simplified models. The methodology of the inverse modeling development for climate responses is then presented and applied to a group of four unheated monumental buildings in The Netherlands and Belgium. Finally, the approach is evaluated and conclusions are drawn.

Literature

Due to developments in information technology, research into simplified models has decreased. However, over time it has become clear that simplified models have several benefits over complex models including user-friendliness, ease of application and speed of calculation [2, 3]. The response factor method and lumped capacitance method are suitable for simplified modeling. More recently, linear parametric models and neural network models have also been used.

Neural network models, e.g. [4] can be classified as black box models. Their parameters have no direct physical meaning, but their output is generated by hidden layers (black box) from the input. Some models are referred to as grey box models. Linear parametric models are examples from the field of simplified building models [5]. The linear model itself is a black box model, but the parameters can be determined using physical data [6]. Some researchers stress the importance of simplified models with physical meaning [7], so called white box models. The lumped capacitance model can be classified as a white box model. Another advantage of this approach is the representation of building elements using R (resistance) and C (capacitance), according to the electrical analogy, which makes a graphic representation of the model possible. Most of the simplified building models are based on this approach.

There are three approaches to create a simplified model: (i) create a detailed comprehensive model from known building properties and then perform a model order reduction technique, e.g., [8]; (ii) create a simplified model directly from building properties, e.g., [9]; (iii) create a simplified model and identify the parameter values with an inverse modeling technique [10]. The first technique is obviously the most labor-intensive: detailed construction properties have to be identified together with a methodology for simplifying an existing model. The lumped capacitance model can be used for this model order reduction [4] and neural network models can be used to filter out unimportant parameters [5], a stage known as pruning. The second technique is faster, but requires a validated strategy to identify appropriate parameters; it is therefore difficult to achieve good results. A methodology for incorporating multiple walls into one single order model has, however, been demonstrated [11]. The final approach is not labor-intensive and identification of the model parameters is achieved

with an optimization algorithm. This technique can be used with the lumped capacitance model [12] neural network model [5], and linear parametric model [13]. The final technique is used for the work in this paper.

State space models

A linear model is often sufficient to accurately describe the system dynamics and, in most cases, is the first to be applied [14]. State space models are linear time invariant (LTI) models. State space models are models that use state variables to describe the system dynamics by a set of first order differential equations. To understand the concept of state space, think of the system as spanning a space where the axes (i.e., dimensions, i.e., orders) represent the state variables. Even if some of the system's differential equations are higher order, they should be converted to multiple first order equations. The state of the system can be represented as a vector within that space. The system of first order differential equations can be represented according to:

$$\dot{x}(t) = A_x(t) + B_u(t)$$
$$y(t) = C_x(t) + D_u(t)$$

The first part of this equation is known as state equation where $\mathbf{x}$(t) is the state vector and $\mathbf{u}$(t) is the input vector. The second equation is referred to as the output equation. $\mathbf{A}$ is the state matrix, $\mathbf{B}$ is the input matrix, $\mathbf{C}$ the output matrix and $\mathbf{D}$ the direct transition matrix.

The main advantage is that the calculation speed is very rapid, especially compared to solving the differential equations with a variable step algorithm (e.g. ode23 in MATLAB). To show this advantage, a first order RC-network is simulated as a state space model and with the ode23 routine for different simulation periods. The results are shown in table 1.

The results show the huge advantage of the state space model regarding simulation time. While the simulation time increases almost linearly when using the ode23 routine to solve the differential equation, the simulation time of the state space model is less predictable. However, the state space model has a very limited calculation time of half a second on an ordinary computer (i5-processor), particularly if the task requires a repeated simulation for a long period, e.g., 100 years.

The next stage is the thermal and hygric modeling. Due to limitations of space, the work of Kramer is summarised [15]. He investigated several thermal models including solar irradiation. Several hygric models have also been developed and tested. In this paper, we present the optimal models from Kramer's perspective [16].

Table 1. Calculation time of state space and ode23 for different periods in MATLAB

	1 month time [s]	1 year time [s]	10 year time [s]	100 year time [s]
Ode 23	5	89	–	–
State space	0.016	0.016	0.050	0.45

The thermal model is shown in figure 1. There are thermal capacitances for the interior (C_{int}), indoor air (C_i) and envelope (C_w). The sun irradiation is connected to C_{int} (interior) and C_i (indoor air). Thermal resistances represent ventilation ($1/G_{fast}$), wall to external air ($1/G_w$), wall to indoor air ($1/G_i$) and indoor air to interior constructions ($1/G$). See the appendix for the ODEs and state space matrices.

The hygric model is shown in figure 2. The hygric capacitances and resistances are analogous to the thermal network, but the driving force is vapor pressure rather than temperature. See the appendix for the ODEs and state space matrices.

Inverse modeling

Inverse modeling is the inverse of traditional modeling. In traditional modeling, the system is known and the output is unknown. By modeling the system, the output can be simulated. In inverse modeling, the output is known (e.g., measured), but little is known about the system's parameters. The objective is to identify the parameter values of the model by repeatedly trying different parameter values and comparing the simulated output with the measured output.

The goal is to minimise the simulation error, formulated as an objective function (e.g., summed squared error). The process of finding the parameter set which minimises the objective function is called optimization. If the solution space includes multiple minima, the goal is to find the global minimum, called global optimization.

There are many different solvers, each having advantages and disadvantages. One important aspect is whether a solver is gradient-based or gradient-free. Gradient-based solvers are the most efficient at finding a minimum quickly. However, the solution space should be smooth and continuous. If not, the solver fails. The second aspect is whether the solver handles constraints or if it is
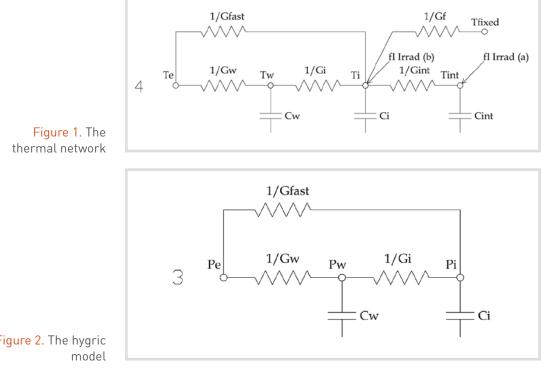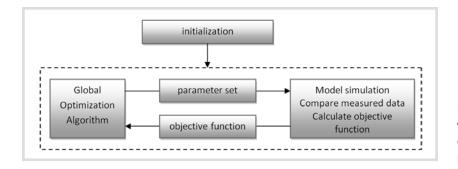

Figure 1. The thermal network

Figure 2. The hygric model

only intended for unconstrained problems. The inverse problem in this research is a typical example of a constrained problem since all variables are not allowed to be negative. Moreover, constraining the problem helps in finding the global minimum since it scales down the solution space. The third aspect is whether a solver is deterministic or stochastic: all solvers are deterministic except for the Genetic Algorithm.

To maximize the speed of the optimization process, see figure 3, all calculations which do not need to be repeated are executed in the initialization step: preparing climate data, include measured data, set constraints and set initial values. Then the optimization algorithm determines the parameter set, the first time it is the initial value vector, and passes the parameter set to the function file: the function file includes the model and simulates the model with the given parameter set and calculates the objective function by comparing the simulated output with the measured data. The objective function is passed to the Global Optimization Algorithm that calculates the new parameter set which is likely to minimize the objective function.

Subsequently, the identified building model can be used: (i) for simulations with other outdoor climate files; (ii) to assess the influence of adding insulation by adjusting a parameter; (iii) to assess the energy performance with different climate installations by coupling the identified building model to heating, ventilation and air-conditioning models.

Results for a group of unheated monumental buildings

An important validation method is the performance assessment of the developed models on multiple buildings: by fitting both the thermal and hygric models to these buildings, their general performance is tested. General applicability is an important aspect in this study. It is important to choose a strategic set of buildings and rooms to gain maximum added value from this validation method. The following were included in the set: (i) a room surrounded by a water canal; (ii) a room with a large thermal and hygric mass; (iii) a room with significant sun irradiation; (iv) a room with sun irradiation on the roof but without windows; (v) rooms with ground contact and no sun irradiation.

The physical aspects of the buildings and rooms and the reasons for their inclusion are explained in the next section. The performance per room is visualized in graphs and then explained. The performance of the rooms is compared by three performance criteria (Mean Squared Error, Mean Absolute Error and Goodness of Fit) at the end of the section. Figure 4 presents the monumental buildings involved in the study.

Castle of Amerongen – Washing room

The washing room is situated in the basement of the castle of Amerongen. The castle is surrounded by a canal and the external walls of the washing room are in direct contact with water. The basement has been flooded many times. The performance of the thermal model is shown in figure 5 (top). The model performs well over the seasons resulting in a good fit. The detail at the right side of the figure shows that the delicate fluctuations of the measured signal are not reproduced by the model, which is beneficial: the sensors have an accuracy of plus or minus 0.5 K meaning that the observed fluctuations are covered by the uncertainty of the measurement. The reason for these delicate fluctuations is unclear and considered to be unimportant for the performance assessment of the model. The performance of hygric model 3 is shown in figure 5 (bottom). There seems to be a problem analogous to the thermal model observed earlier: the signal lies occasionally above but mostly below the measured signal. The result is that the model cannot be fitted accurately. A new parameter was introduced for
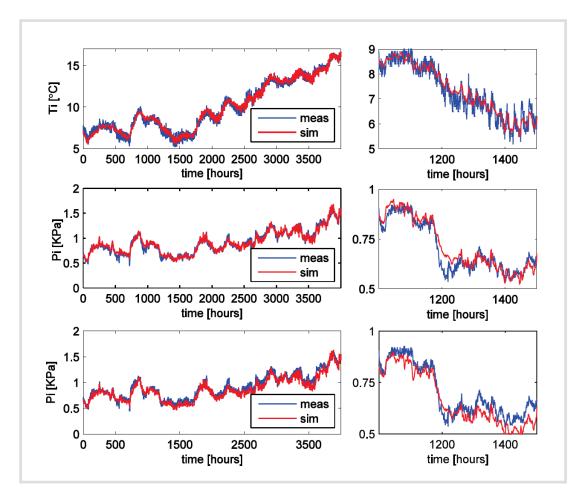

Figure 5. The thermal model (top), hygric model with additional fixed vapour pressure node in model (middle) and hygric model without fixed pressure (bottom) fitted to washing room

the hygric model, which is analogous to the thermal model: a node with a fixed vapour pressure. The performance of this hygric model with fixed vapour pressure is shown in figure 5 (middle). The fixed vapour pressure improves the fit significantly. The necessity of such a fixed vapour pressure suggests the existence of a vapour source. Physically, the external wall connected to the canal is analogous to the thermal situation with ground contact.

Castle of Gaasbeek – Scockaert chamber

The Scockaert chamber is on the second floor of the castle of Gaasbeek (Belgium). It has windows which allow a significant amount of solar radiation into the room. The room is richly decorated with antique furniture, which adds to the thermal and hygric capacity. The difficulty here is the irregular disturbances by visitors. Because this effect cannot be captured by a linear time invariant model, the Scockaert chamber is a good candidate for the model's performance assessment. The result of the thermal model is shown in figure 6 (top). The overall performance is good but some incidental measured peaks are observed which are not reproduced in the model. These peaks might be a result of internal heat sources like visitors. The result of the hygric model (with fixed vapour pressure node) is shown in figure 6 (bottom). The same observation holds as for the thermal result. The overall performance is good, but identical series of peaks are not reproduced. These peaks are due to inputs which are not included, e.g., moisture production by visitors.

Castle of Gaasbeek – Gothic chamber

The Gothic chamber is also situated on the second floor of the castle of Gaasbeek. The room is richly decorated and contains a large suite of furniture and decorations which contribute chiefly to the hygric capacity, but also to the thermal capacity. This room is also frequently visited by tourists. The performance of the thermal model is shown in figure 7 (top). The incidental peaks are less intense compared with those in the Scockaert chamber, but are
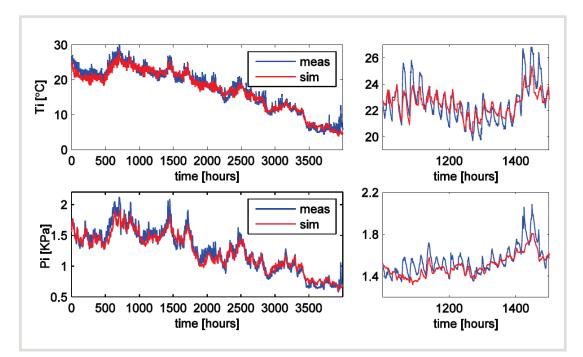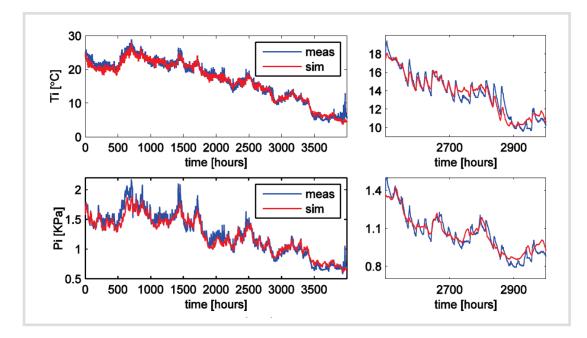

Figure 6. The thermal model (top) and hygric model with additional fixed vapour pressure node (bottom) fitted to Scockaert chamber

still visible. The detail at the right side of the figure shows that the model reproduces the measured signal accurately. The delicate rapid fluctuations present in the measurements of the washing room are completely absent in the measurements of the Gothic chamber.

The hygric model performance is shown in figure 7 (bottom). The overall performance is good, but small disturbances which are not reproduced are probably due to time-variant phenomena. The phenomena which could change over the seasons are not necessarily sources of error, such as the possible use of sun blinds in summer.

Castle Keukenhof – the loft

Castle Keukenhof is situated a few kilometers from the Dutch coast and so is exposed to a sea climate. The room under consideration is the loft, directly beneath the roof. This room is interesting specifically because of the risk of it overheating in summer. This situation offers the potential to test the model rigorously as the influence of sun irradiation is significant though there are no windows.

The thermal model performance is visualized in figure 8 (top). The risk of overheating is presented clearly and is reproduced well by the model. Although the sun irradiation is modeled by four input signals, each representing the sun irradiation on vertical walls oriented respectively to the north, east, south and west, the sun irradiation on the roof and the resulting heat flow to the loft is simulated correctly. This significant heat flow from the sun results in an indoor temperature of up to 35 °C in summer. The detail at the right side of the figure demonstrates how accurately the model's output has been fitted to the measured temperature. The performance assessment of the hygric model is shown in figure 8 (bottom). The hygric reproducibility is poor. The indoor temperature and moisture content (or vapour pressure) fluctuate heavily. These fluctuations could not be reproduced with the sole input of the outdoor vapour pressure. This case offers interesting potential for follow-up research.

St. Bavo cathedral – south transept

St. Bavo cathedral is in Gent, Belgium. The building consists of several parts, e.g., the choir, the entrance, the transepts, most of which are connected. The building is totally free-standing and has a huge thermal and hygric mass.

The measurements to which the model has been fitted were collected by a sensor in the south transept. The south transept includes a huge window with colored glass which is oriented to the south, resulting in a significant amount of incoming solar irradiation. The performance of the thermal model is shown in figure 9 (top). The measured indoor temperature is reproduced very accurately, which can also be visualized clearly in the detailed graph on the right. Although there are visitors, their influence on the indoor climate seems to be small due to the large dimensions of the cathedral. The performance of the hygric model is shown in
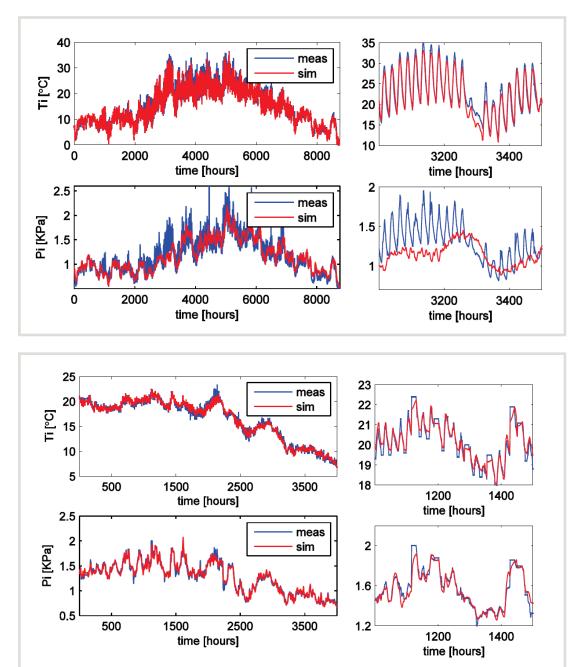

Figure 8. Thermal model (top) and hygric model with additional fixed vapour pressure node (bottom) fitted to Keukenhof loft

Figure 9. The thermal model (top) and hygric model with additional fixed vapour pressure node (bottom) fitted to St. Bavo Cathedral, South transept

figure 9 (bottom). The measured signal is reproduced perfectly by the model. Again, although there are visitors, they hardly influence the indoor moisture content due to the vast space of the cathedral. Furthermore, the quality of the measurements is high, without signal noise.

Performance assessment of the methodology

This section deals with the performance assessment of the models and methods employed. The performance of the models relates to two factors:

• how accurately the measured signal can be reproduced
• how accurately the parameters can be identified (not included in this paper).

This implies a contradiction. Usually, the rule holds that a higher order model with more parameters yields a higher accuracy. On the other hand, more parameters result in a higher uncertainty in parameter identification [15].

To be able to compare and rate how accurately the different models can reproduce a measured temperature or vapor pressure, three performance criteria are used: the MSE (Mean Squared Error), MAE (Mean Absolute Error) and FIT (goodness of FIT).

The MSE is calculated according to,

$$MSE = \frac{1}{N} \sum_{k=1}^{N} (y' - y)^2$$

where y' is the measured signal and y is the simulated signal. The MAE is calculated according to,

$$MAE = \frac{1}{N} \sum_{k=1}^{N} |y' - y|$$

Table 2. Results of fit summarized in three performance criteria (MSE, MAE & FIT)

Building	Room	Thermal model 4a			Hygric model 3		
		MSE	MAE	FIT	MSE	MAE	FIT
		[°C²]	[°C]	[%]	[Pa²]	[Pa]	[%]
Amerongen	Washing room*	0.09	0.24	91	4938	58	72
	Washing room				2468	39	81
Gaasbeek	Scockaert chamber	1.03	0.73	84	5369	57	77
	Gothic chamber	0.66	0.59	87	5316	56	78
Keukenhof	Loft	1.33	0.88	84	23785	113	58
St. Bavo Cathedral	South transept	0.17	0.32	91	1870	32	86
	South transept**	0.74	0.69	81			
Museum Gevangenpoort	Dungeon of pain	0.30	0.41	87	3686	47	84
	Iron chamber	0.10	0.26	82	462	18	85
	Knight chamber	0.34	0.45	88	3710	47	84
	Stock loft	1.41	0.96	81	6954	65	78

*model without node for fixed vapour pressure
**no solar input

The Goodness of Fit is calculated according to,

$$FIT = 100 \cdot \left(1 - \frac{norm(y' - y)}{norm(y' - \bar{y}')}\right)$$

norm(y) is the Euclidean length of the vector y, also known as the magnitude. The equation above therefore calculates in the numerator the magnitude of the error between measured and simulated signal. This is divided by the denominator, calculating how much the measured signal fluctuates around its mean. Consequently, the Goodness of Fit criterion is robust with respect to the fluctuation level of the signal. All three are used independently in several studies, e.g. [16, 17, 18]. However, the benefits of using the three together are stressed elsewhere [10]. For example, the MSE gives more weight to larger errors. Consequently, it is a good criterion to express the amount of large errors. The MAE expresses the overall mean error.

Conclusions

It is concluded that this approach is very promising for obtaining physical models and parameters of indoor climate responses. In addition, the use of state space models results in extremely fast processing times as the simulation of 100 years of hourly data takes less than a second on an ordinary computer.

Appendix

The ODEs of the thermal model are:

$$C_w \frac{dT_w}{dt} = G_w(T_e - T_w) - G_i(T_w - T_i)$$
$$C_i \frac{dT_i}{dt} = G_i(T_w - T_i) - G_f(T_i - T_f) - G_{int}(T_i - T_{int}) + G_{fast}(T_e - T_i) + \overrightarrow{fl} \cdot \overrightarrow{Irrad}(b)$$
$$C_{int} \frac{dT_{int}}{dt} = G_{int}(T_i - T_{int}) + \overrightarrow{fl} \cdot \overrightarrow{Irrad}(a)$$

The State Space matrices of the thermal model are:

$$A = \begin{bmatrix} \frac{-G_w - G_i}{C_w} & \frac{G_i}{C_w} & 0 \\ \frac{G_i}{C_i} & \frac{-G_i - G_f - G_{int} - G_{fast}}{C_i} & \frac{G_{int}}{C_i} \\ 0 & \frac{G_{int}}{C_{int}} & \frac{-G_{int}}{C_{int}} \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{G_w}{C_w} & 0 & 0 & 0 & 0 & 0 \\ \frac{G_{fast}}{C_i} & \frac{fl_1}{C_i} & \frac{fl_2}{C_i} & \frac{fl_3}{C_i} & \frac{fl_4}{C_i} & \frac{G_f}{C_i} \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$C = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \qquad D = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

The ODEs of the hygric model are:

$$C_w \frac{dP_w}{dt} = G_w(P_e - P_w) - G_i(P_w - P_i)$$
$$C_i \frac{dP_i}{dt} = G_i(P_w - P_i) + G_{fast}(P_e - P_i)$$

The State Space matrices of the hygric model are:

$$
A = \begin{bmatrix} \frac{-G_w - G_i}{C_w} & \frac{G_i}{C_w} \\ \frac{G_i}{C_i} & \frac{-G_i - G_{fast}}{C_i} \end{bmatrix} \quad B = \begin{bmatrix} \frac{G_w}{C_w} \\ \frac{G_{fast}}{C_i} \end{bmatrix} \quad C = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \quad D = \begin{bmatrix} 0 \\ 0 \end{bmatrix}
$$

References

[1] CIBSE, TM36, Climate Change and the Indoor Environment: Impacts and Adaptation, Chartered Institute of Building Services Engineers, London (2005).

[2] Wang, S., and Chen, Y., 'A novel and simple building load calculation model for building and system dynamic simulation', Applied Thermal Engineering 21 (2001) 683–702.

[3] Mathews, E., Richards, P., and Lombard, C., 'A first-order thermal model for building design', Energy and Buildings 21 (1994) 133–145.

[4] Mustafaraj, G., Lowry, G., and Chen, J., 'Prediction of room temperature and relative humidity by autoregressive linear and nonlinear neural network models for an open office', Energy and Buildings 43 (2011) 1452–1460.

[5] Mustafaraj, G., Chen, J., and Lowry, G., 'Development of room temperature and relative humidity linear parametric models for an open office using BMS data', Energy and Buildings 42 (2010) 348–356.

[6] Jimenez, M., Madsen, H., and Andersen, K., 'Identification of the main thermal characteristics of building components using Matlab', Building and Environment 43 (2008) 170–180.

[7] Kopecký, P., Experimental Validation of Two Simplified Thermal Zone Models, Tampere, Finland (2011).

[8] Gouda, M., Danaher, S., and Underwood, C., 'Building thermal model reduction using nonlinear constrained optimization', Building and Environment 37 (2002) 1255–1265.

[9] Nielsen, T., 'Simple tool to evaluate energy demand and indoor environment in the early stages of building design', Solar Energy 78 (2005) 73–83.

[10] Balan, R., Cooper, J., Chao, K.M., Stan, S., and Donca, R., 'Parameter identification and model based predictive control of temperature inside a house', Energy and Buildings 43 (2011) 748–758.

[11] Fraisse, G., Viardot, C., Lafabrie, O., and Achard, G., 'Development of a simplified and accurate building model based on electrical analogy', Energy and Buildings 34 (2002) 1017–1031.

[12] Wang, S., and Xu, X., 'Simplified building model for transient thermal performance estimation using GA-based parameter identification', International Journal of Thermal Sciences 45 (2006) 419–432.

[13] Moreno, G., Trejo-Perea, M., Castañeda-Miranda, R., Hernández-Guzmán, V.M., and Herrera-Ruiz, G., 'Modeling temperature in intelligent buildings by means of autoregressive models', Automation in Construction 16.5 (2007) 713–722.

[14] Ljung, L., System Identification: Theory for the User. 2nd edition, Prentice-Hall, Upper Saddle River, New York (1999).

[15] Kramer, R.P., The application of inverse modeling for the prediction and characterization of indoor climates and energy performances, MSc Report, Eindhoven University of Technology (2012) (unpublished).

[16] Boaventura Cunha, B., Couto, C., and Ruano, A., 'Real time estimation of dynamic temperature models for greenhouse environment control', Control Engineering Practice 5.10 (1997) 1473–1481.

[17] Crabb, J., Murdoch, N., and Pennman, J., 'A simplified thermal response model', Building Services Engineering Research and Technology 8 (1987) 13–19.

[18] Frausto, H., Pieters, J., and Deltour, J., 'Modeling greenhouse temperature by means of auto regressive models', Biosystems Engineering 84.2 (2003) 147–157.

Authors

Jos van Schijndel is Assistant Professor at the Building Physics and Systems group of the Eindhoven University of Technology. Currently, his research is focused on computational building physics. His passion is creative computational modeling using state of the art scientific software and experimental validation in real buildings. Email: a.w.m.v.schijndel@tue.nl

Henk Schellen is Associate Professor for Building Physics and Systems Unit at Eindhoven University of Technology. Email: h.l.schellen@tue.nl.

Rick Kramer is a PhD candidate at the Department of the Built Environment, Eindhoven University of Technology. Email: r.p.kramer@tue.nl

Licence

The moving fluctuation range – a new analytical method for evaluation of climate fluctuations in historic buildings

Stefan Bichlmair, Kristina Holl and Ralf Kilian

Abstract

Indoor climate has a strong influence on the preservation of interiors; the effects on the surfaces of valuable furnishing and artworks are of major concern. To evaluate the indoor climate thorough measurements have to be made. But how should this data be analysed? There are some established and some newer methods to evaluate measured climate data. The authors present here a new analytical method and its application on measured climate data from unheated historic buildings such as the King's House on the Schachen, Linderhof Palace and the small rural church of St. Margaretha in Roggersdorf. Within this new method a moving average is used for the analysis of short-term fluctuations of relative humidity and temperature. As a result a moving fluctuation range of relative humidity is obtained for example the maximum range in an hourly moving interval of 24 hours compared to the commonly used values of equidistant daily cycles. Conventional methods of statistical analysis are compared to the new method for different time periods. Advantages and disadvantages of the different approaches are discussed. A further result of this new method is the better understanding of the indoor environment and improved evaluation of measured data. A perspective is presented on possible applications of the moving fluctuation range method for investigations on the real physical behavior of collections due to fluctuations in relative humidity. The moving fluctuation range method can also be used in building simulation tools for evaluation of indoor climate conditions for collections.

Introduction

For several years there has been a major debate about the right values and allowable ranges of relative humidity (RH) and temperature for the indoor climate in museums and other buildings housing artworks. The two main arguments against maintaining a constant indoor climate of 50 % relative humidity and a temperature of 20 °C all year (which can only be achieved by an air-conditioning system), are the high risk of damage to old buildings with minor insulation standards, particularly in the winter and the huge energy demands. Beyond the knowledge that no fluctuations will cause no damage to artworks there is no strong physical evidence for these rigid values.

The discussed ranges of indoor climate are usually coupled to specific time periods. A major research question is the relevance and effect of short-term fluctuations of temperature and relative humidity on works of art. But how is a short-term fluctuation defined? How stable is the indoor environment in unheated historic buildings? When the data is analysed, the time periods considered generally correspond to annual, seasonal and daily periods and

some in between, like weeks or months. The real physical behavior of materials is often not considered or only in a generalised way. Each material and composite material has its unique material characteristics and therefore has a different sensitivity to changes in humidity and temperature. Depending on their composition, dimension and thermal as well as hygric inertia some composite materials are affected immediately by short-term fluctuations. This paper highlights the effect of short-term fluctuations of relative humidity and temperature and proposes a new method of data analysis.

Climate fluctuations

The definition for allowable values was derived from a questionnaire on typical climates in museums. There are still many questions about the damaging effects to artworks stored in a particular climate. One damage mechanism is caused by the hygroscopic behavior of materials. The typical behavior of hygroscopic materials is to shrink and swell with changes in relative humidity and temperature. The aim of giving set points and allowable ranges of fluctuations for indoor climates is to prevent artworks from damage. Usually, very general recommendations are given, referring to the overall indoor environment. Short-term fluctuations of relative humidity and temperature can have a negative impact on thin sensitive hygroscopic materials in particular but also on the surfaces of artworks independent of their volume. Burmester [1] summarises the state of the art for museums. Short-term fluctuations of plus or minus 2.5 % RH and plus or minus 1 K within one hour and plus or minus 5 % RH within one day should not be exceeded. For several materials fluctuations of plus or minus 5 % RH during one week are still bearable. These specifications are given for the conditions of air in the vicinity of the objects.

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Handbook [2] prescribes for climate class AA, allowable short-term fluctuations of plus or minus 5 % in relative humidity and plus or minus 2 K for temperature, based on a set point of an annual average space gradient. In Class B, fluctuations of plus or minus 10 % RH and plus or minus 2 K for precision-controlled climates are permitted. Additional recommendations for seasonal changes are made. No further specific descriptions on the basis of a short-term fluctuation or seasonal changes are referred to. Further classifications are made without special requirements for buildings with no precision control. Although there are additional classifications, descriptions and information for buildings, there is no further distinction or advice for historic buildings with no climate control. Kilian [3] gives a detailed description and distinguishes between requirements for museum buildings with climate control and listed buildings and monuments.

Holmberg [4] specifies that 15 % is an acceptable daily range of relative humidity variation in unheated buildings based on observations made on a wooden door. Many more definitions and specification are available in the literature. Common in these descriptions is an allowable range for relative humidity and temperature for a certain time interval. However, some elements are not defined within the specifications: why are these time cycles selected for evaluation, and how are data measured?

Measurement and analysis of short-term cycles
Measurement of the room climate

One typical method to evaluate the prevailing indoor climate is to measure the condition of indoor air with its parameters relative humidity and temperature. There are two main constraints in measuring these parameters: positioning and accuracy of the sensors.

As mentioned above the ASHRAE handbook [2] assumes some space gradients for the deviation of microclimates between the location of the sensors and object, in contrast Burmester [1] discusses values in the vicinity of the object. For general statements about the indoor climate, the equipment should be installed in the middle of the room. For an assessment of the condition of an object and to make judgements about risks posed by the environment, measurements near the artwork are necessary. However, all buildings with natural or controlled climates have many diverse microclimates which can differ significantly from the climate measured at a certain point, like the middle of a room. These microclimates would have to be considered separately.

The accuracy and response of the sensors is also important to proper measurement and evaluation of a climate. It is useless to discuss certain values or tight RH ranges if the calibration, accuracy and response of sensors are not sufficient for the evaluation in question; see also Camuffo [5] and Brown [6].

Existing methods for analysis of measured data to short-term fluctuations

Only a proper analysis of measured data can provide reliable statements concerning the prevailing climate and its potential to damage artworks. A common method is to evaluate the measured data for short-term fluctuations within a daily cycle. The maximum difference in relative humidity gives the maximum fluctuation for this day. With this derived data a graph can be drawn showing only the daily fluctuation range in a timeline for each day, or as a histogram plot sorted from the highest value to the lowest.

A newer method for the evaluation of indoor climate is given by EN 15787 [7]. Based on experimentally observed changes in painted wood, a method is introduced with a monthly moving average of relative humidity. This 30-day average stands for the seasonal cycle. A short-term fluctuation is defined as the difference between the measured data and the monthly moving average. On this average line, the 7th and 93rd percentile of measured data (equal to a standard deviation of 1.5) are defined as the border lines for the maximum distance of the acceptable range of short-term fluctuation (Figure 5). This method offers a combined evaluation of short- and long-term fluctuations. The monthly moving average shows the seasonal trend. This evaluation seems a better fit for the real behavior of hygroscopic materials with a certain thickness, for example painted wooden panels, than the usually rather generalised guidelines.

Yet it is not clear to which materials, combinations of materials or material characteristics and thickness this analysis method applies and if it is sufficient for the evaluation of damage potential.

Material characteristics of artworks

The right time period over which to evaluate the damage potential of the environment on artworks depends on the kind of artwork under consideration. From a physical perspective, there is no correlation between moisture sorption and a daily cycle. The moisture sorption from and to the air is mainly driven by the difference between the moisture equilibrium of the material and the relative humidity.

As different objects are made of different materials or also composite materials the reaction to a change in climate depends on the physical characteristics of the materials themselves. Diffusion-resistant parts like the paint layer in a pastose oil painting will behave differently from the very permeable canvas. Experiments show an immediate reaction in weight-change of a sensitive artwork like a painting on cardboard to a change in relative humidity (Figure 1).

Concerning the hygrothermal characteristics of artworks, only a few values are available, for example, the water vapour diffusion resistance or isotherms for reconstructed historic composite materials from Wehle [8], Worch [9] and Rachwał [10]. Reliable data for combined inhomogeneous materials and their uncertainty ranges are completely unknown.

Time cycles and measuring periods

Typical periods for analysing climate data are one hour, one day, several days, one week, one month and one year. The one-day period is an alternating cycle of relative humidity depending on day and night. In most regions of the world, a one-year period is also a real cycle with seasonal changes in relative humidity and temperature overlaying the daily cycle. Cycles of one hour, several days, one week or month are mainly arbitrary and serve as an aid to describe intermediate cycles. They give the typical cycles of human anthropology, but not necessarily of material behavior. The different cycles serve as an aid to match to the different time constants of different materials. For example, a sheet of parchment or an oil painting on cardboard will react very quickly to changes in RH and therefore shorter time intervals should be chosen for evaluation compared to a painted panel as mentioned above.
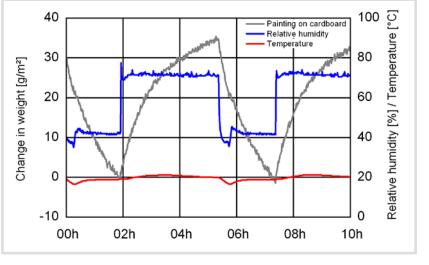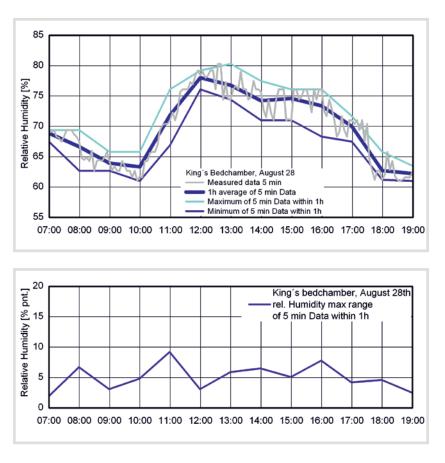

Figure 1. Change in weight for an oil painting on cardboard, when subjected to cyclical changes in relative humidity from 40 to 70 % at 19 to 20 °C

Figure 2. The graph shows a typical day in the summer in the King's bedchamber in Linderhof Palace. In the morning, the windows were opened just before the visitors came in. Both influences have a certain impact in relative humidity and cause strong fluctuations. The blue and light blue graphs show the maximum value within one hour and the minimum relative humidity. The dark blue centre graph shows the hourly average of the 5-minute measured data (grey line).
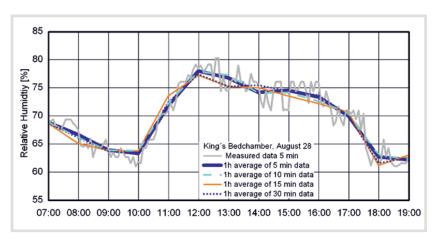

Figure 3. The relative humidity fluctuations reach up to 9 % RH within one hour with 5-minute measured data

There is also a question about the most appropriate duration of a condition in relation to the time intervals being studied. What is the correct time duration of a condition in relation to 24 hours? A common time interval is one hour but consideration of different durations may also be useful. But how often should the indoor air conditions be measured within one hour to get sufficient information?

Figure 2 shows a graph of measured data of relative humidity in the unheated Linderhof Palace for one day during opening time. Due to open windows and entering visitors the relative humidity changes very quickly. The five-minute measured data (grey line) are compared to their hourly average value (dark blue line). Additionally two lines are shown in the graph with the maximum and minimum RH for each hour of the five-minute data. The relative humidity changes quite quickly in this example. There are short-term fluctuations up to 9 % RH per day though for the most part values of about 5 % RH fluctuation can be observed (Figure 3).

A variation in average values depending on the number of data used per hour is shown in figure 4. The average values are calculated from 5-minute interval data by taking every second, third and sixth value. This means the average value is calculated with 10 minutes measured data interval and also with 15 minutes, and 30 minutes. That gives an estimation of the necessary measuring frequency for one-hour values and how much information gets lost. The maximum deviation to the 5-minute average value to the average line made of 30-minute measured values is nearly to 2 % RH in this example. For a longer period deviations of up to 3 % RH were observed for the King's bedchamber. This is only of interest for investigations of short-term fluctuations. The long-term means of both average values are

Figure 4. Average values with different time intervals are compared with each other. The average lines are based on the same measured data. With only two measured data in one hour too much information gets lost. In this example a deviation of 2 % RH occurs compared with the average line of 5-minute data
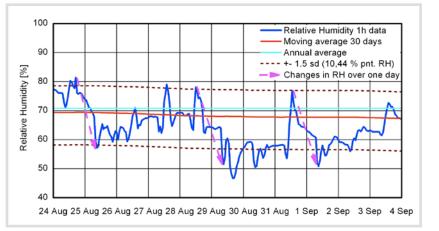
almost matching. The example of the unheated Linderhof Palace with more than 3000 visitors shows a rapidly changing indoor climate. It also shows possible deviation of relative humidity values depending on the frequency of measurement. During closing times without visitors and less ventilation before and after opening time we can observe only small fluctuations with less dependency on measuring frequency.
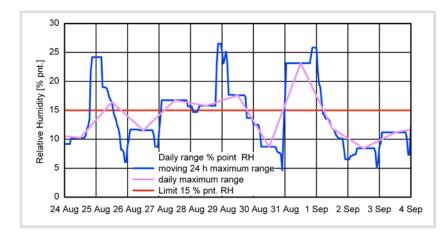
For buildings like Linderhof with large variations in visitor numbers and ventilation rates, short measuring intervals of 5 or 10 minutes are necessary to get sufficient information.

A newly developed method for evaluation of measured data for short-term fluctuations

For further evaluation of the data we will examine a longer time interval. Figure 5 shows a one-hour average value of relative humidity based on data measured over 5-minute intervals in Linderhof Palace. The light blue graph shows the annual average of a one-year period from December 2009 to December 2010. The red line is the 30-day moving average and the broken line shows the 1.5 standard deviation (sd) as recommended in EN 15787. The 1.5 sd for the measured year equates, for the King's bedroom, to plus or minus 10.4 % RH forming a relatively 'safe' zone around the moving average, relatively 'safe' because the standard is meant to be used only if no damage is present, which is not the case for Linderhof Palace. The three dashed arrows indicate a vast change in RH which exceeds a one-day period. If we analyse a one-day period on its maximum range of RH we cannot recognise changes

Figure 5. The blue line shows the one-hour average value of the five-minute measured RH in the King's bedchamber in Linderhof Palace. The 7th and 93rd percentile or 1.5 sd around the moving average are shown [7]. The light red arrows show vast changes in RH over a one-day period

exceeding one day. By moving this 24-hour period by an hourly step it is possible to make changes exceeding one day visible.

Figure 6 compares both methods of equidistant analysis and an hourly moving 24-hour interval. The blue line shows the hourly moving maximum fluctuation range within 24 hours. The light red graph shows the fluctuation range within equidistant 24 hours from 1:00 am to 0:00 pm for 11 days. The maximum range of RH in a moving 24-hour interval in figure 6 is up to 9 % RH higher than with the equidistant daily method calculated. The examined data is a one-hour average value of relative humidity based on a 5-minute interval of data measured in the King's bedchamber in Linderhof Palace in 2010.

Examples of climate data examined with the new method of the moving 24-hour maximum fluctuation range of relative humidity
Case study: Linderhof Palace

For a detailed description of the climate in Linderhof palace see [11]. Figure 7, left graph shows the maximum range of relative humidity analysed with two methods. One method is the moving 24-hour interval (blue line), the other method is the commonly used daily equidistant interval (light red line) with 365 values. The data were collected in the King's bedroom in Linderhof Palace from December 2009 to December 2010. Each fluctuation beyond 15 % RH is seen as critical for the original furnishing in Linderhof Palace. If each event beyond 15 % RH range (red line) is counted, 8 % of the days in one year exceed this range. With the moving maximum fluctuation range, fluctuations beyond the critical line
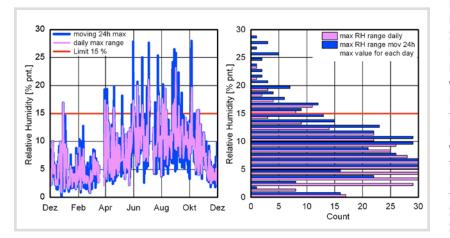
on 12 % of the days within this year are counted. Much stronger fluctuations, by up to 10 % are made visible by the new method. The histogram in figure 7 counts each maximum fluctuation per day. For the 24-hour moving fluctuation, if a vast single fluctuation happens over two days, a double count may occur. This phenomenon is explained in figure 5 by the arrows. The calculated mean value of all RH fluctuation beyond 15 % of the new method is 4.0 % RH higher when compared with the calculated mean RH fluctuation of the common equidistant method. With the new method 1.5 times as many occurrences beyond 15 % RH can be detected compared to the common method.
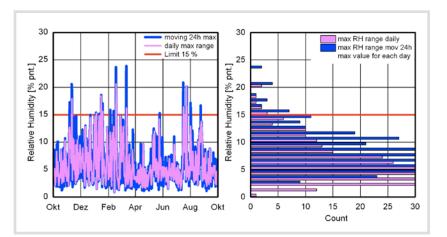
Case study: the Turkish Hall in the King's House on Schachen

The King's House on Schachen built by King Ludwig II. of Bavaria (1869–1872) is situated in the Bavarian mountains at a height of 1876 m above sea level. It is open to visitors for four months during summer, the rest of the time it is closed due to the snow. Intensive conservation assessments [12] as well as a building simulation and climate studies have been done [8], [13]. Applying the new moving 24-hour method shows that the values exceeding the limit are much lower than in Linderhof Palace. Still there are some occurrences beyond the 15 % fluctuation range, which may be dangerous for the historic interiors in the Turkish Hall. With the new method, 2.1 times as many occurrences beyond 15 % RH can be detected compared with the common method. The method with the moving 24-hour interval also reveals stronger fluctuations than the equidistant method. The maximum distance between the two methods is 7.7 % RH at a fluctuation beyond 15% RH (Figure 8). The difference of the mean RH ranges beyond 15 % between the two methods is 3.0 % RH.

Case study: Church St. Margaretha in Roggersdorf

The small church of St. Margaretha in Roggersdorf was built in the seventeenth century and is still unheated. The indoor climate shows high average humidity [15] and very large fluctuation ranges of up to 37 % RH points. The method with the moving 24-hour interval reveals stronger fluctuations than the equidistant method. Applying the new method, 1.9 times as many events with fluctuations beyond 15 % RH can be detected compared with the common method (Figure 9). The maximum distance between the two methods is 13 % RH at a fluctuation beyond 15 % RH. The difference of the mean RH ranges beyond 15 % RH between the two methods is 3.4 % RH.

Figure 8. Maximum range of relative humidity within a 24-hour moving interval for each hour (blue line) and with an equidistant interval of one day for each day (light red line). The data were taken from the Turkish Hall in the King's House on Schachen from October 2006 to October 2007
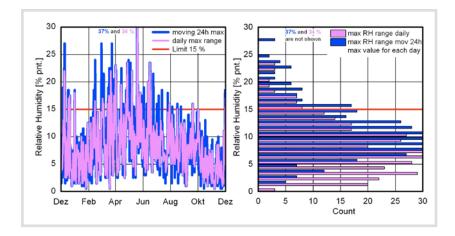
Figure 9. Maximum range of relative humidity within a 24-hour moving interval for each hour (blue line) and with an equidistant interval of one day for each day (light red line). The data was measured in Roggersdorf from December 2004 to December 2005

Conclusion and outlook

The new method of evaluation of short-term fluctuations with a moving fluctuation range makes the real maximum fluctuation of a particular climate visible. In all of the three examples there are up to two times more fluctuations beyond 15 % RH detectable when compared with the equidistant daily method, see table 1. Also, much wider short-term fluctuations were revealed, up to 13 % RH higher with a mean difference of mean values of RH ranges of up to 4 % RH, see table 2. The new method has been successfully applied to assess the indoor climates of three unheated monuments with different local ambient climates and visitor numbers. With the new method, the real climate conditions

Table 1. Results of three examples on evaluation of maximum fluctuation range in relative humidity with two different methods, number of days exceeding 15 % RH fluctuation

	number of equidistant 1-day range ≥ 15 % RH	number of moving 24-h range ≥ 15 % RH	difference	factor of difference (multiplier)
	[days]	[days]	[days]	[-]
Schachen	9	19	10	2.1
Roggersdorf	36	68	32	1.9
Linderhof	30	45	15	1.5
mean multiplier				1.8

Table 2. Results of three examples on evaluation of maximum fluctuation range in relative humidity with two different methods, mean difference and maximum value

	mean difference between equidistant 1-day range minus moving 24-h range in values ≥ 15 % RH	Maximum difference of RH range between the two methods
	[% RH]	[% RH]
Schachen	3.0	7.7
Roggersdorf	3.4	13.0
Linderhof	4.0	11.0
mean multiplier	3.5	–

can be captured more accurately. This is an important conclusion when assessing damage caused to artworks by short-term environmental fluctuations. For the examples of the Linderhof Palace, the King's House on Schachen and the Church of St. Margaretha in Roggersdorf the limit of changes considered to pose a risk was set to 15 % point RH due to the condition assessments which had been undertaken on these buildings. Here the analysis was done for relative humidity but the method can also be used for the examination of temperature differences. Broader fluctuation values should be expected here too. The new method has also been used successfully to validate simulated data generated during a simulated climate exercise for preventive conservation purposes at the Linderhof Palace [14].

Further investigations are necessary to determine the limits of non-hazardous short-term fluctuations as evidence. The new method to analyse climate data should be further developed as a standard tool. This work will need to include a critical review of the definition of short-term fluctuation, the response of different materials and the applicability of experimental data obtained by step functions in climate chambers in comparison with real climates.

References

[1] Burmester, A., 'Der moderne Museumsbau: Konzept des Überlebens oder überlebtes Konzept?' in Zeitschrift für Kunsttechnologie und Konservierung 11/2, Worms am Rhein (1999) 192–200.

[2] American Society of Heating, Refrigerating and Air-Conditioning Engineers, 'Chapter 23: Museums, galleries, archives and libraries', in ASHRAE Handbook – HVAC Application (SI), ed. M.S. Owen, ASHRAE, Atlanta (2011).

[3] Kilian, R., 'Umgang mit Klimadaten im Vergleich zwischen Museen und Denkmalpflege', in Preventive Conservation - Von der 'Passiven Konservierung' zum Risk Management' - Erfahrungen und Konzepte zur Präventiven Konservierung in der gegenwärtigen restauratorischen Praxis, ed. A. Jeberin, Workshop at the FHTW-Berlin, 1 March 2007, Berlin (2007).

[4] Holmberg, J. G., 'Technical classification of museum buildings ICOM-ICAMT 1989', in EUROCARE Eureka Project EU 140, EU 1378 PREVENT, Preventive Conservation, Report No.7 from Swedish Partners (1997).

[5] Camuffo, D., Microclimate for Cultural Heritage. Developments in Atmospheric Science 23, Elsevier, Amsterdam (1998).

[6] Brown, J.P., 'Hygrometric measurement in museums: calibration, accuracy, and the specification of relative humidity', in Preventive Conservation: practice, theory and research: preprints of the contributions to the Ottawa Congress, 12-16 September 1994, ed. A. Roy, P. Smith, International Institute for Conservation, London (1994) 39–43.

[7] EN 15757, Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials (2010).

[8] Wehle, B., Simulation des Raumklimas unter Berücksichtigung der Feuchtepufferungseigenschaften des Türkischen Saales im Königshaus am Schachen, Diplomarbeit, Rosenheim (2010).

[9] Worch, A., 'Zu Ausgewählten feuchtephysikalischen Eigenschaften von Ölgemälden auf Leinwand', in WTA Almanach, WTA-Publications, München (2007) 503–522.

[10] Rachwał, B., Bratasz, Ł., Łukomski, M., and Kozłowski, R., 'Response of wood supports in panel paintings subjected to changing climate conditions', Strain 48.4 (2012) 366–374.

[11] Bichlmair, S., and Kilian, R., 'Room Climate in Linderhof Palace. Impact of ambient climate and visitors on room climate with a special focus on the bedchamber of King Ludwig II', in Developments in climate control of historic buildings, Proceedings of the international conference: Climatization of historic buildings, state of the art, Linderhof Palace, 2 December 2010, ed. R. Kilian, T. Vyhlidal, T. Broström, Fraunhofer IRB Verlag, Stuttgart (2011) 53–60.

[12] Holl, K., Der Türkisches Saal im Königshaus am Schachen. Die Erhaltung der Ausstattung in Hinblick auf das Raumklima, Diplomarbeit, München (2008).

[13] Kilian, R., Holm, A., Radon, J., and Künzel, H. M., 'Assessment of the climatic stability of a royal mountain chalet – The King's House on the Schachen', in WTA-Almanach, WTA-Publications, München (2008).

[14] Bichlmair, S., Kilian, R., Krus, M., and Sedlbauer, K., 'Building simulation modeling of the historic building Linderhof Palace taking account visitors', in Proceedings of eSIM, IBPSA Canada, Halifax (2012).

[15] Kilian, R., 'Statistische Untersuchungen der Klimaschwankungsbreite in unterschiedlich genutzten Kirchenbauten', in WTA Almanach, WTA-Publications, München (2007).

Authors

Stefan Bichlmair is a member of the working group 'Preventive Conservation and Heritage Preservation' at the Department of Indoor Environment at Fraunhofer Institute for Building Physics IBP, Holzkirchen. Email: stefan.bichlmair@ibp.fraunhofer.de

Kristina Holl is a member of the working group 'Preventive Conservation and Heritage Preservation' at the Department of Indoor Environment at Fraunhofer Institute for Building Physics IBP, Holzkirchen. Email: kristina.holl@ibp.fraunhofer.de

Ralf Kilian is head of the working group 'Preventive Conservation and Heritage Preservation' at the Department of Indoor Environment at Fraunhofer Institute for Building Physics IBP, Holzkirchen. He is also the scientific coordinator of the EU Project 'Climate for Culture'. Email: ralf.kilian@ibp.fraunhofer.de

In recent years heritage professionals have been engaged in animated debate about appropriate climatic conditions for collections held in museums, galleries and historic buildings. The emotive issues in this debate have included inflexible standards, unsuitable modern architecture, unreasonable loan conditions, predicted climate change and rising energy costs. Scientific attempts to measure and predict changes to art objects have been challenged as they do not relate to the ways that art objects are perceived and valued.

The 35 papers in this volume investigate what is known and what is not known about suitable environmental conditions for cultural heritage collections. They present the most significant recent research on this subject, informed by a major international conference, held at the Pinakothek der Moderne in Munich from 7 to 9 November 2012.