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Climate Control in the Face of Climate Change: Reducing Carbon Footprints in Museums

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Abstract

With mounting pressures to decrease carbon emission and the growing scarcity of funds, museums must look at their current practices. The standards for climate control in museums are based on challenges museums face in the early twentieth century and relied on limited information and technology. As museums begin to face new challenges due to climate change, the old standards must be reevaluated. Most museums rely on a Heating, Ventilation, and Air Conditioning (HVAC) system to maintain strict set-points, however, such systems are expensive and energy intensive. This limits their availability to small and historical museums that do not have the infrastructure to install them. The current standards are also centered on Western European standards. This thesis will look at the history of climate control in museums and how museums can reduce their dependence on energy-inefficient systems in the face of global climate change.

Contents

Introduction

Scientists predict that in the next few years extreme weather events will increase. Following the 2018 heatwave in Europe, temperatures are predicted to rise in Europe the following years[1]. Increased natural disasters related to climate change are also predicted and will disproportionately affect Asia and Africa[2]. These growing threats put museum collections in jeopardy. Studies have been done to protect permanent cultural sites but there is a gap in studies for museums[3]. Museums cannot just simply move their collections in the face of sudden natural disasters and moving objects will not solve long term climate-related issues that the museum would face.

Museums cannot wait for other institutions and industries to lower energy expenditure while museums continue to have high carbon emissions. Museums are already facing issues globally with decreased funding and trouble reaching temperature and relative humidity set-points. Museums outside of Western Europe and North America, as well as small museums and those housed in historic buildings, have difficulties reaching the standardized set-points even when expensive systems are put into place. Large museums that do have extensive climate control systems or Heating, Ventilation, and Air Conditioning (HVAC) systems are often running them at a high cost and low energy efficacy. In order to lower carbon emissions, these

[1] Amin Moazami, Vahid M. Nik, Salvatore Carlucci, and Stig Geving, "Impacts of Future Weather Data Typology on Building Energy Performance- Investigating Long-Term Patterns of Climate Change and Extreme Weather Conditions," *Applied Energy* 238 (March 15, 2019): 698, https://www.sciencedirect.com/science/article/pii/S0306261919300868 (accessed March 28, 2019).

[2] Reinmar Seidler, Katie Dietrich, Sarah Schweizer, Kamaljit S. Bawa, Shashikant Chopde, Farrukh Zaman, Anshu Sharma, Sumana Bhattacharya, Laxmi P. Devkota, and Sarala Khaling, "Progress on Integrating Climate Change Adaptation and Disaster Risk Reduction for Sustainable Development Pathways in South Asia: Evidence from Six Research Projects," *International Journal of Disaster Risk Reduction* 31 (October 2018): 92, https://www.sciencedirect.com/science/article/pii/S2212420918305223 (accessed March 28, 2019).

[3] T. Mazurczyk, N. Piekielek, E. Tansey, and B. Goldman, "American Archives and Climate Change: Risks and Adaptation," *Climate Risk Management* 20 (January 1, 2018): 112, https://www.sciencedirect.com/science/article/pii/S2212096318300135 (accessed March 28, 2019).

strict standards should be evaluated to see if they are still vital moving towards a future with more extreme temperature fluctuations.

First, it is vital to understand why museums require strict interior climate control to protect their collection. Fluctuations in temperature and relative humidity (RH) are detrimental to objects and museums without any climate control often suffer from increased cases of mold and pollutants. However, the current set-points for ideal temperature and RH have not changed much since their original inception in the 1940s. There are flaws in the creation of the current set-points such as limited technology and lack of scientific evidence. Originally, heating was introduced primarily for human comfort. Systems were limited in how much they could change temperatures and RH control was nonexistent in the beginning. This is why we must look at the history of climate control systems in museums. Using heating and cooling systems in museums for the preservation of objects was a great discovery but not one without struggles along the way. Even today museums will face problems when installing climate control systems. The current set-points we used were created under very specific scenarios that mostly focused on England during World War II, which played a role in the creation of set-points when museums moved their artwork to temporary locations.

Today museum collections are also facing threats in the form of increased flash floods and wildfires according to the Federal Emergency Management Agency (FEMA)[4]. In light of these threats, it is vital that we look at the current set-points and standards with a critical eye. Museums cannot completely abandon using climate control systems, instead, we determine if strict set-points are beneficial to the museum as reducing daily fluctuations. New technology is constantly being released as well and we much ask if the set-points would be scientifically

[4] Mazurczyk et al., "American Archives and Climate Change: Risks and Adaptation," 112.

justified when museums are able to control temperature to a much greater extent with today's HVAC systems. The current set-points are also very Eurocentric and only focus on traditional museum settings. We will look at a case study in China where different methods of climate control are used in an attempt to reduce costs and protect recently unearthed artifacts. Finally, we will discuss the different methods museums may be able to implement. There is not one solution that will fit all museums. Each museum is different with its own unique climate control problems. Protecting cultural heritage and the environment are not exclusive to each other and museums can reduce energy use in a way that is beneficial to the museum and its collection.

Chapter 1: The Necessity of Climate Control in Museums

The success of object preservation depends on the environment in which an object resides. Museums combat deterioration, such as fading and warping, through the use of internal climate control within their buildings. Preventative conservation mitigates risks to the collection before damage occurs[5]. Damage from temperature changes and relative humidity (RH) is slow and may not be noticeable until significant damage has already occurred. However, all materials require a different temperature and RH range to avoid damage and museums with varied objects must find a climate that protects as many diverse objects in the collection as possible[6].

Over the years museums have developed different methods and set-point to control the climate in the collection storage and exhibition area. Climate control is currently primarily controlled with Heating, Ventilation, and Air Conditioning (HVAC) systems which use set-points developed in European, especially British museums in the first half of the twentieth century. For decades, these standards went unquestioned until recent years when awareness arose of how energy consumption drives climate change. Museums began to question the effectiveness of strict set-points and continuously running HVAC systems.

Relative Humidity cannot become too high or too low in museum settings. Relative Humidity (RH) is different from absolute humidity. RH is the amount of water vapor in the air compared to the maximum absolute humidity at a particular temperature. Relative Humidity increases with temperature as warm air can hold more water molecules than cold air. When the

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[5] Edgar Neuhaus, "A critical look at the use of HVAC systems in the museum environment." In *Climate for Collections, Standards and Uncertainties*, eds. Jonathan Ashley-Smith, Andreas Burmester and Melanie Eibl (Munich: Archetype Publications Ltd, 2013): 117.

[6] David Erhardt, Charles S. Tumosa and Marion F. Mecklenburg, "Applying science to the question of museum climate." In *Museum Microclimates Conference* eds. Tim Padfield and Karen Borchersen (Copenhagen: The National Museum of Denmark, 2007): 11.

humidity reaches 100%, water will condense from the air[7]. The rate of change or speed of temperature and humidity changes affects the severity of the damage to objects[8]. Drastic changes in humidity or temperature are the most damaging and can happen quickly, even overnight[9]. Museums install humidity control for the benefit of their collections to protect them from extreme ranges. Sensors can turn on or off systems as the ranges approach levels outside the correct scope much like heating systems do for temperature[10].

When talking about damage to a collection, there are three main types to consider: chemical, biological, and mechanical. The area where items are stored and the material composition of an object can have a great effect on the impact of each type of damage. Chemical damage refers to damage and decay done by molecular reactions. Pollutants, for example, will damage the collection as they react with the objects. Some pollutants are released by collection objects themselves such as off-gassing of plastics and metal corrosion. While museums are unable to stop the process completely, reactions can be slowed by controlling the conditions where objects are stored and displayed[11]. Keeping temperatures low in object storage areas can slow down off-gassing and filters can prevent external contaminants from entering the collection.

Biological damage is done by any organism such as mold, insects, or other pest species like mice. Objects made from organic material are affected the most by biological damage as they provide a food source for museum pests. Mold and insects thrive in warmer climates so a

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[7] Marta Leskard, "A sustainable storage solution for the Science Museum Group," *Science Museum Group Journal* 4 (Autumn 2015), http://dx.doi.org/10.15180/150405 (accessed June 20, 2018).
[8] Museums & Galleries Queensland, Museums & Galleries of NSW, Regional and Public Galleries Association of NSW, and Regional Galleries Association of Queensland. *A Practical Guide for Sustainable Climate Control and Lighting in Museums and Galleries* (Sydney, Australia: International Conservation Services and Steensen Varming, 2014): 44.
[9] William Rose, "Effects of climate control on the museum building envelope," *Journal of the American Institute for Conservation* 33, 2 (1994), https://www.jstor.org/stable/3179428 (accessed September 25, 2018).
[10] Rose, "Effects of climate control on the museum building envelope."
[11] Museums & Galleries Queensland, *A Practical Guide for Sustainable Climate Control and Lighting in Museums and Galleries*, 10.

warm and humid environment in the museum will draw them to the collections. The museum needs to keep storage areas cool and dry to avoid infestation[12].

Mechanical damage references physical damage including cracks, breaks, melting or warping. Mechanical damage can be the result of mishandling but may also stem from environmental conditions. If temperatures are too high, wax objects can soften, if they are too low, paper and leather can become brittle. Drastic changes can cause wood to expand and contract faster than the painted surface on it, causing damage to the paint. Relative humidity can also cause damage when too high, warping objects from increased moisture or causing objects to dry out and become brittle when too low[13].

The museum building still needs to be comfortable for humans so a museum cannot set its environmental parameters too extreme. Balances are determined to be a condition between the ideal for slowing object deterioration and inhabitable comfort levels for visitors and staff. In some cases, specialized storage areas are needed for fragile objects but most objects can coexist in the human comfort range[14]. The needs of people and collections do overlap. The primary overlap is improved air quality and for humans the ability to stay comfortable in the building for many hours. The collections need improved air quality through stable temperature and relative humidity levels and fewer pollutants[15]. Some objects, such as photographs or heavily damaged items should be kept separate due to their condition or material[16].

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12 Museums & Galleries Queensland, *A Practical Guide for Sustainable Climate Control and Lighting in Museums and Galleries*, 8.
13 Museums & Galleries Queensland, *A Practical Guide for Sustainable Climate Control and Lighting in Museums and Galleries*, 8.
14 Museums & Galleries Queensland, *A Practical Guide for Sustainable Climate Control and Lighting in Museums and Galleries*, 5.
15 Mattias Legnér, "On the Early History of Museum Environment Control-Nationalmuseum and Gripsholm Castle in Sweden, c. 1866-1932," *Studies in Conservation* 56, 2 (2011): 133, http://dx.doi.org/10.1179/sic.2011.56.2.125 (accessed September 25, 2018).
16 Erhardt, Tumosa, and Mecklenburg, "Applying science to the question of museum climate," 15.

The location of the building and the physical properties of it, such as insulation and building materials will play a large role in the internal environment of the museum. Historic buildings, for example, usually warm and cool faster than modern buildings because they are less insulated. Buildings with interior climate issues will most likely have structural damage as well such as mold or water damage[17]. External conditions like shade and outside temperatures can affect the inside temperature and humidity. Buildings often have some kind of buffer such as insulation in place, but it should be kept in mind that the bigger the difference between the two climates, the more difficult it is to maintain a stable interior climate[18]. This relationship is the building envelope or the boundary between exterior and interior conditions. Any part of the building that separates the inside and outside is part of the envelope. Large differences between interior and external conditions will put stress on the building envelope[19]. For example, trying to maintain high RH levels in cold climates will put a strain on the building and HVAC system. Condensation can start to form causing damage to the building and potentially affect the collection[20]. Building materials will have an effect on heat and moisture transfer. For instance, wood and brick will hold moisture for weeks even after an HVAC system implemented. Objects and the environment will always have moisture exchange so when interior climates are set to rigid conditions, it can cause stress on the envelope as external temperatures change. The stress can cause damage to the building and wear out the HVAC system quicker, so a range of temperatures and RH is usually used over a single set-point[21]. The RH control also has limits to

[17] Z. Huijbregts, R.P. Kramer, M.H.J. Martens, A.W.M. van Schijndel, and H.L. Schellen, "A proposed method to assess the damage risk of future climate change to museum objects in historic buildings," *Building and Environment* 55, (2012): 44-45.
[18] Museums & Galleries Queensland, *A Practical Guide for Sustainable Climate Control and Lighting in Museums and Galleries*, 13.
[19] Rose, "Effects of climate control on the museum building envelope."
[20] Erhardt, Tumosa, and Mecklenburg, "Applying science to the question of museum climate," 12.
[21] Rose, "Effects of climate control on the museum building envelope."

what the system can handle[22]. Many museums adapt a Seasonal Adjustment Movement to reduce cost and strain on their system. The set-points for the system are altered to be closer to the external conditions slowly over the course of the seasons without sacrificing the collection or human comfort[23].

Air conditioning and HVAC systems are used to keep the interior climate of a building within a set range of temperature, humidity, and air quality. The goal is to create a microclimate in which the conditions and location are clearly defined[24]. HVAC systems also remove air contaminants. Museums are recommended by the European Standard EN 13779 to use the second strictest level of Indoor Air Quality or IDA 2. IDA 1 is recommended for hospitals and similar institutions. This standard is used across the European Union and other regions[25]. Under these regulations, a range for the temperature to be used in museums is determined to prevent short-term fluctuations. In European Standard EN 15757 there is an expansion on the guidelines to include taking historical climate of the museum into account[26]. This means that although it is recommended against by several standards it is okay to allow small fluctuations and divergence from the standard set-points in museums if the collection is consistently exposed to those

[22] Erhardt, Tumosa, and Mecklenburg, "Applying science to the question of museum climate," 13.
[23] Museums & Galleries Queensland, *A Practical Guide for Sustainable Climate Control and Lighting in Museums and Galleries*, 42-44.
[24] Jerry Shiner, "Trends in microclimate control of museum display cases." In *Museum Microclimates Conference* eds. Tim Padfield and Karen Borchersen (The National Museum of Denmark, 2007): 267.
[25] Luis Perez-Lombard, Jose Ortiz, and Ismael R. Maestre, "The map of energy flow in HVAC systems," *Applied Energy* 88 (2011): 5021-5022, https://www.sciencedirect.com/science/article/pii/S030626191100448X (accessed June 20, 2018).
[26] Joanna Ferdyn-Grygierek, and Krzysztof Grygierek, "HVAC Control Methods for Drastically Improved Hygrothermal Museum Microclimates in Warm Season," *Building and Environment* 149 (2019): 91, https://www.sciencedirect.com/science/article/pii/S0360132318307546 (accessed December 20, 2018).

conditions in the past[27]. This might be beneficial for museums that face challenges with controlling RH due to large variation in seasonal weather[28].

Air is cooled or warmed in a building by an economizer. It ventilates the building by mixing air from outdoors with indoor air. The incoming air is mechanically cooled or heated when it is outside the range of the temperature the system is set to[29]. Warmer air is cooled in an air conditioning unit by passing air over a cool coil. The air temperature and humidity lower as it passes through the system[30]. The efficiency of the system is determined by the Air Exchange rate, or how fast outdoor air replaces indoor air. If a building is well insulated, the rate will be lower and the system will work better[31]. Systems used by museums need to be able to control both[32]. Improper indoor conditions will cause deterioration of objects and can be caused by external environments, visitor numbers, and lighting. There are seasonal and daily variations to these factors, for example, it is easier to stabilize temperature when there are no visitors in the exhibition hall[33]. The type of material affects the rate of deterioration due to these factors[34].

Having an air conditioning or heating system can indirectly control humidity through controlling temperature. Heating will dry the air, while water washing airflow filtering systems can add humidity. Combinations can be used to create the desired interior environment[35]. Air conditioning will use latent cooling to remove humidity and sensible cooling to lower

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[27] Ferdyn-Grygierek and Grygierek, "HVAC Control Methods for Drastically Improved Hygrothermal Museum Microclimates in Warm Season," 97.
[28] Hawra Sharif-Askari and Bassam Abu-Hijleh, "Review of museums' indoor environment conditions studies and guidelines and their impact on the museums' artifacts and energy consumption," *Building and Environment* 143 (2018): 187, https://www.sciencedirect.com/science/article/pii/S0360132318304207 (accessed December 20, 2018).
[29] "Perfecting the art of energy efficiency," *Air Conditioning, Heating & Refrigeration News* 247, 11 (2012).
[30] Rose, "Effects of climate control on the museum building envelope."
[31] Museums & Galleries Queensland, *A Practical Guide for Sustainable Climate Control and Lighting in Museums and Galleries*, 42.
[32] Rose, "Effects of climate control on the museum building envelope."
[33] Ferdyn-Grygierek and Grygierek, "HVAC Control Methods for Drastically Improved Hygrothermal Museum Microclimates in Warm Season," 90.
[34] Sharif-Askari and Abu-Hijleh, "Review of museums' indoor environment conditions studies and guidelines and their impact on the museums' artifacts and energy consumption," 188.
[35] Erhardt, Tumosa, and Mecklenburg, "Applying science to the question of museum climate," 11.

temperature. HVAC systems will also introduce pollutants through air flow unless they have air filters in place to remove them. This is also due to the changes of RH that the HVAC system introduces which can speed up chemical reactions in the air of the building. Most filters will only remove large particles, however[36].

Having a heating system set too high, for example, can cause condensation on windows damaging the building[37]. When heating systems were first introduced to museums, the damage was seen in collections due to the drop in humidity. The Alte Pinakothek in Munich, Germany needed to humidify its rooms after installing heating because the panel paintings became damaged from the dry air[38]. This was not just an isolated incident with heating as it was first introduced. Modern museums still struggle to maintain proper temperatures and RH when first installing a system. It is important to make sure that the changes introduced are slow to avoid damage[39].

The need for climate control becomes apparent when comparing two castles in Northern Europe. Each building was highly susceptible to mold growth due to their location and high relative humidity. A 17th-century castle in the Netherlands has a limited heating and dehumidification system that is on a room-by-room basis due to its thick stone walls. The controlled climate in the interior is set to a minimum temperature of 10°C and dehumidification at a maximum of 7 kg per day. During the time measured, the building varied in average temperature from 1°C and 26°C and relative humidity between 40% and 80%. Being stored in

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[36] Sharif-Askari and Abu-Hijleh, "Review of museums' indoor environment conditions studies and guidelines and their impact on the museums' artifacts and energy consumption," 188.
[37] Rose, "Effects of climate control on the museum building envelope."
[38] Melanie Eibl and Andreas Burmester, "Learning from history. Historic indoor climate conditions and climate control strategies." In *Climate for Collections, Standards and Uncertainties,* eds. Jonathan Ashley-Smith, Andreas Burmester and Melanie Eibl (Munich: Archetype Publications Ltd, 2013): 219.
[39] Joanna Ferdyn-Grygierek, "Monitoring of indoor air parameters in large museum exhibition halls with and without air-conditioning systems," *Building and Environment* 107 (2016): 114, https://www.sciencedirect.com/science/article/pii/S0360132316302797 (accessed October 24, 2018).

the castles for decades exposed the objects to large RH fluctuations and damaged them in the process before the buildings were turned into museums. In the Netherlands, the museum stabilized its collection and prevented the largest threat, mold growth. Meanwhile, a 13th-century castle in Belgium does not have any HVAC system. There, the temperature varied between 3°C and 30°C and the relative humidity between 40% and 90%. The castle in Belgium could not control new mold growth like the Dutch castle was able to do even with a limited HVAC system[40].

The HVAC also needs to be set in the human comfort range. Also called the human thermal comfort, it is the range of temperature and humidity in which humans are most comfortable. The range is determined to be the conditions with the least amount of dissatisfaction amongst visitors and guests[41]. Museums are ultimately community centers so while preserving objects is their main function, spaces where people work and visit need to be set to be comfortable conditions which limits the set-points a museum can choose to store objects at.

Having an HVAC system is beneficial to museums; however, such systems are a recent invention. Many museums need to control their interior climate without using an HVAC system especially in locations outside of Western Europe and the United States. The current standards only take into account past conditions of Western Museums and museums that can afford expensive HVAC systems. However, these museums are not the museums that will be the most affected by climate change. While having a climate control system in the museum is important it is vital to be critical of their origin and energy consumption, as the energy use does not always

[40] Huijbregts, et al., "A proposed method to assess the damage risk of future climate change to museum objects in historic buildings," 44-45.
[41] Museums & Galleries Queensland, *A Practical Guide for Sustainable Climate Control and Lighting in Museums and Galleries*, 11.

create a benefit large enough for the museum to justify the use of large complex systems. As seen in the castle case studies, smaller HVAC systems can create a large change in the museum's climate without using a lot of energy. In order to understand our current set-points, we need to look at the history of heating and cooling in museums.

Chapter 2: A History of HVAC Use and the Trial and Error of Methods

There is evidence of climate-controlled storage from historical periods as early as ancient Greece and Egypt. Egyptian tomb makers used advanced engineering techniques and tight seals to create an environment discovered to be stable for thousands of years[42]. Current developments in museum climate control were mostly based on the development of HVAC systems in museums in the United States and Western Europe[43]. Originally, there were no special conditions for housing objects other than preventing mechanical damage. However, specific temperature and humidity range standards were created through observations by museums. Air conditioning started to appear in museums in the 1800s. Before this, there was no way to control the climate other than through building design, fireplaces or windows. Consequently fragile objects had to be kept in boxes or cases[44]. Heating was installed first before cooling or humidity control. A popular system was the Perkins Ovens which used thin pressurized pipes of hot water heated by passing the pipes through a brick oven. The water was heated beyond boiling point and as it passed through pipes around the building, it would give off heat through vents in the floor. The British Museum installed Perkins Ovens in 1835. However, Perkins Ovens were prone to overheating and could explode due to pressure in the pipes so they required constant supervision to run properly[45]. Museums also would install several different types of heating systems to different parts of the museum. Central Heating Systems later used a boiler and radiators to move steam to heat the building. This allowed museums to heat the building effectively, but it also

[42] Shiner, "Trends in microclimate control of museum display cases," 267.
[43] Legnér, "On the Early History of Museum Environment Control-Nationalmuseum and Gripsholm Castle in Sweden, c. 1866-1932," 125.
[44] Erhardt, Tumosa, and Mecklenburg, "Applying science to the question of museum climate," 13.
[45] Legnér, "On the Early History of Museum Environment Control-Nationalmuseum and Gripsholm Castle in Sweden, c. 1866-1932," 128.

caused pollution that damaged the collections[46]. The new heating systems, as well as newly introduced gas lighting, damaged leather and paintings in London museums during the nineteenth century. The solution was to increase ventilation in the museum in addition to creating enclosed display cases for objects. Paintings were also sealed with glaze in the National Gallery in London[47]. A bit later in 1915, the Cleveland Museum of Art introduced a plenum air system to the building that used a water spray to clean air[48].

The first air cooling systems developed during the 1900s[49]. Buildings in general during this time period were cooler and more humid than today though as central heating dries the interior air[50]. The Boston Museum of Fine Arts first installed a system that controlled temperature and humidity in 1908. Based on its observations, the museum created a range for RH of 55% to 60% for its collection in 1910[51]. This range was used by other museums but was often also dependent on the capacity of the systems they were using.

A scientific approach to conservation began in the 1920s after World War I. Museums moved objects during the war to buildings less likely to be damaged by strikes, but the chosen locations were often inappropriate for object storage causing damage anyway. The British Museum opened a conservation lab shortly after the war to repair objects that were stored in damp conditions. During this time, an increased interest in controlling conditions grew in museums[52]. In the 1930s, air conditioning was still very expensive. New museum buildings

[46] Eibl and Burmester, "Learning from history. Historic indoor climate conditions and climate control strategies," 219.
[47] Shiner, "Trends in microclimate control of museum display cases," 267.
[48] Legnér, "On the Early History of Museum Environment Control-Nationalmuseum and Gripsholm Castle in Sweden, c. 1866-1932," 126.
[49] Legnér, "On the Early History of Museum Environment Control-Nationalmuseum and Gripsholm Castle in Sweden, c. 1866-1932," 125.
[50] Legnér, "On the Early History of Museum Environment Control-Nationalmuseum and Gripsholm Castle in Sweden, c. 1866-1932," 125.
[51] Erhardt, Tumosa, and Mecklenburg, "Applying science to the question of museum climate," 13.
[52] Legnér, "On the Early History of Museum Environment Control-Nationalmuseum and Gripsholm Castle in Sweden, c. 1866-1932," 125.

could adopt the new systems, but many buildings did not have the infrastructure to house the units[53]. Museums focused only on controlling temperature unless the museum experienced humidity-based problems. The National Gallery in London and Harvard's Fogg Museum at the time both ran tests to monitor humidity-based damage but costs limited their ability to install a full system. The National Gallery in London experienced blistering on paintings due to humidity changes especially during the winter months when the museum's heat was on. The Fogg Museum conducted a similar study with similar results but could not afford a new climate control system[54]. Cost restraints are still a driving factor for decision making in museums today.

An example of early museum HVAC developments could be seen in the Nationalmuseum in Stockholm, Sweden. Built in the 1860s, the museum housed the royal collections which were recently made available to the public. Original the collection was stored in the royal palace. The new museum building had several stories including a basement and attic all with a lot of windows. The museum architects were aware during construction that many of the works from the palace needed conservation and aimed to create stable conditions in the new museum. The two upper floors housed the collections and exhibition space and no electric lighting was used prior to 1930[55]. The Nationalmuseum installed their first heating system in 1862 as part of the interior construction instead of part of the museum building. The Perkins Ovens installed used highly pressured hot water that is pushed through pipes around the museum[56]. However, the system created several problems for the museum, the air became very dry causing cracks to appear on wood panels. A supervisor also had to be hired to live in the basement of the museum

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[53] Shiner, "Trends in microclimate control of museum display cases," 268.
[54] Legnér, "On the Early History of Museum Environment Control-Nationalmuseum and Gripsholm Castle in Sweden, c. 1866-1932," 126.
[55] Legnér, "On the Early History of Museum Environment Control-Nationalmuseum and Gripsholm Castle in Sweden, c. 1866-1932," 126.
[56] Legnér, "On the Early History of Museum Environment Control-Nationalmuseum and Gripsholm Castle in Sweden, c. 1866-1932," 128.

in order to prevent the pipes from overheating. This was a common problem with the Perkins Ovens as water needed to be heated to 150-200°C and passed through thin pressurized pipes. In addition, the ovens only heated the exhibition spaces and the offices and workspaces would reach frigid temperatures in the winter until 1916 when the museum installed electric radiators and a steam boiler for the roof. The new systems did not heat the building adequately and snow often piled on the roof. At the time, the collections had also grown and objects were stored in the basement and attic, neither location had been designed to house collections. In addition, the heat only operated during working hours and the cold temperatures at night resulted in water condensing in the skylights and windows. To prevent the galleries from flooding, water had to be collected in tanks with as much as 1000 liters of water collected a night[57]. By 1923, the problems at the Nationalmuseum become even more obvious. The pipes from the Perkins Ovens deposited dirt on freshly painted walls and paintings in close proximity to the pipes were damaged. This caused the museum to install a new system in 1931 that filtered and heated air from the outside and to install humidifiers in 1932 to combat excessive drying[58]. This case study shows that even after a museum installs an HVAC system, it can still encounter problems with interior climate control. While heating systems are more sophisticated and not as dangerous, there is still a threat to the collection when installed improperly. Like in the Nationalmuseum, museums today can suffer damage to its collection from its HVAC system. Air conditioning units, for example, can leak causing damage to the structure and to the collections.

More museums including the National Archives and Library of Congress started adapting air conditioning in the 1940s as air conditioning systems improved. After World War II, more

[57] Legnér, "On the Early History of Museum Environment Control-Nationalmuseum and Gripsholm Castle in Sweden, c. 1866-1932," 126-134.
[58] Legnér, "On the Early History of Museum Environment Control-Nationalmuseum and Gripsholm Castle in Sweden, c. 1866-1932," 126-134.

museums began to install HVAC systems. During World War II, the National Gallery of London hid its art collection in slate quarry caves. They discovered the conditions of the cave preserved the art better than those in the gallery. Heating was used to maintain a low RH in the caves but the consistent temperature was natural. While in the caves, the paintings had stopped flaking. After the war, the Gallery installed a system to mimic the conditions in the caves[59]. After the National Gallery and other museums observed that humidity levels were causing damage and only correlated with temperature changes, focus shifted on controlling humidity. Sealed cases also improved to allow for RH control through saturated salts[60]. By the 1960s most museums had some kind of HVAC system in place. The current standards for RH set-points, which will be discussed in the next chapter, are based on these past experiences such as the observations of the London National Gallery and the mechanical limitations of HVAC systems. Systems continuously become more effective as technology improves, and in 1994 the Smithsonian Institution began to develop new guidelines based on computer modeling[61].

The evolution of museum climate control still continues as more museums obtain HVAC systems. Current museums still face problems with newly installed systems and while correct HVAC systems are safer than early heating systems, museum still encounter a trial and error period when introducing new controls into the museum. Furthermore, global climate change was not considered a primary driving factor for museums in the past. Many Governments are placing limitations and restrictions on carbon emission for businesses as a result of the growing recognition of climate change. Museums now need to consider in choosing systems and HVAC units. Museums must now look at their current set-points and evaluate if they are scientifically accurate or only being used because they have worked in the past.

[59] Erhardt, Tumosa, and Mecklenburg, “Applying science to the question of museum climate,” 14.
[60] Shiner, “Trends in microclimate control of museum display cases,” 268.
[61] Erhardt, Tumosa, and Mecklenburg, “Applying science to the question of museum climate,” 14.

Chapter 3: Climate Change vs Climate Control

Museums are required to think about their internal environment differently than one would an office or home[62]. Guidelines put out by the American Society of Heating Refrigeration and Air-conditioning Engineers (ASHRAE) suggest that short-term and seasonal fluctuations can be allowed and provide a grade scale of different classes of climate control. Ranging from D to AA, D represents the lowest amount of control only preventing dampness in the collection area, while AA represents controls where no damage is done to the collection. They suggest that museum set-points be based on the annual average of temperature and relative humidity that the collection has historically been exposed to. There is an algorithm to determine the best set-points with diminishing returns on protecting the collection[63]. The museum should evaluate the risk that climate change will have on the building by looking at past events and their frequency and severity. They should look at three main variables in their assessment according to Giuseppe Forino et al. in their article "A Proposed Assessment Index for Climate Change-Related Risk for Cultural Heritage Protection in Newcastle (Australia)", structural condition, asset fabric condition, and historical damage[64]. External conditions and internal load from visitors and lighting are the two main contributing factors to fluctuations and result in poor HVAC performance and a strain on the museum building envelope. Lighting can increase the temperature in the exhibition hall, although this is less of a problem with LED lights. The presence of visitors can significantly change the temperature and humidity in a room. High

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62 Sharif-Askari and Abu-Hijleh, "Review of museums' indoor environment conditions studies and guidelines and their impact on the museums' artifacts and energy consumption," 186.

63 Rick Kramer, Jos van Schijndel, and Henk Schellen, "Dynamic Setpoint Control for Museum Indoor Climate Conditioning Integrating Collection and Comfort Requirements: Development and Energy Impact for Europe," *Building and Environment* 118 (June 2017): 14–31, https://www.sciencedirect.com/science/article/pii/S0360132317301269 (accessed February 12, 2019).

64 Giuseppe Forino, Jamie MacKee, and Jason von Meding, "A Proposed Assessment Index for Climate Change-Related Risk for Cultural Heritage Protection in Newcastle (Australia)," *International Journal of Disaster Risk Reduction* 19 (October 1, 2016): 239, https://www.sciencedirect.com/science/article/pii/S2212420916301078 (accessed March 28, 2019).

visitor occupancy increases the temperature in museum microclimates and exhibition halls. Even with an HVAC system running, if there are too many visitors in a room the effect will be negated. Main entrance halls particularly suffer from increased temperatures as there is a higher concentration of visitors compared to other parts of the museum[65]. Increased visitor numbers can especially be a problem for museums housed in historic buildings with substandard insulation and small rooms. The smaller spaces mean that there is a higher density of visitors and often the HVAC system is already running less efficiently due to older building material and walls. Museums not used to large crowds will also experience similar increases in temperature if they suddenly receive a large influx of new visitor groups as the location becomes more popular with tourists.

In comparison with the ASHRAE, European standards emphasize the procedure over set-points. The standards discourage short-term fluctuations and suggest too that historic conditions be used[66]. In the case study previously mentioned in chapter one, museum collections housed in medieval churches with no climate control suffered from mold and humidity damage. When an HVAC was added, it relied on historic conditions in museums for the target conditions and was able to improve conditions. Heating systems were introduced for human comfort so that visitors and staff could visit throughout the year. The central heating system however lowered relative humidity and damaged paintings in the castle[67]. The current standards are a compromise of all collection material types. Museums with single-type object collections are rare and it is difficult

[65]Ferdyn-Grygierek and Grygierek, "HVAC Control Methods for Drastically Improved Hygrothermal Museum Microclimates in Warm Season," 90-91.
[66] Ferdyn-Grygierek and Grygierek, "HVAC Control Methods for Drastically Improved Hygrothermal Museum Microclimates in Warm Season," 90-97.
[67] Margus Napp, and Targo Kalamees, "Energy Use and Indoor Climate of Conservation Heating, Dehumidification and Adaptive Ventilation for the Climate Control of a Mediaeval Church in a Cold Climate," *Energy & Buildings* 108 (December 2015): 61.

to choose a set-point that will work with entire collections[68]. The standards used in museums today are not scientifically justifiable and were based on observations in museums but not any actual scientific measurements. Most museums did not have air conditioning until the 1970's when concerns about the conditions in museum buildings grew[69].

The current goal is to create a homogeneous microclimate or an internal environment in which all the spaces in the museum remain within the set parameters for air quality and do not fluctuate between rooms. This is not always possible due to the building envelope and room arrangement. Rooms such as entry halls that are exposed to the external environment will have a different climate than interior rooms despite being heated to the same temperature. At any given time, a museum will have air temperature gradients even if the museum has central heating or cooling because it is impossible to prevent changes in temperature entirely. Heating and cooling is limited by the resources of the museum. Humidifiers, for example, only have a limited capacity and cannot cover a large exhibition hall. The museum would either need to install more humidifiers or a complex central system, yet neither situation is ideal for museums with limited budgets[70]. The conflict between the different environmental conditions needed for the museum puts a strain on the air conditioning and climate control system.[71]

The failure to decrease energy consumption and cost comes from the rigid standards that are set for museum conditions. Passive temperature control can be used especially in new buildings where one can use new materials and designs that increase energy efficiency.

[68] Ferdyn-Grygierek, "Monitoring of indoor air parameters in large museum exhibition halls with and without air-conditioning systems," 113-116.
[69] Hugo Entradas Silva, Fernando M.A. Henriques, Telma A.S. Henriques, and Guilherme Coelho, "A sequential process to assess and optimize the indoor climate in museums," *Building and Environment* 104 (2016): 21-34, https://www.sciencedirect.com/science/article/pii/S0360132316301445 (accessed October 24, 2018).
[70] Joanna Ferdyn-Grygierek, "Indoor environment quality in the museum building and its effect on heating and cooling demand," *Energy and Buildings* 85 (2014): 33-36.
[71] Museums & Galleries Queensland, *A Practical Guide for Sustainable Climate Control and Lighting in Museums and Galleries*, 8.

However, it is more difficult to install passive measures into older buildings. A conservator should be the one to ultimately decide on the conditions for the museum and, if possible, engineers can create a system that fits the needs of a diversified collection[72]. Historic buildings that house museums will install HVAC systems at the cost of high expenses and inefficacies. While museum collections may be preserved, the actual building can suffer damage from the installation and drastic changes in internal temperature[73]. Historic buildings often tend to have poor hygrothermal exchange rates, meaning that the building envelope lacks the proper insulation and exchange rate between internal and external temperature that modern buildings have. Yet, many museums are housed in historic buildings due their aesthetic and historic value. The HVAC system with standard controls is not able to adjust quickly enough to the fluctuations and does not maintain the proper set-points. The system will either always be at full capacity or it will start to overcompensate for the changes resulting in a high-energy use[74]. Climate control techniques are constantly evolving. Historic museums were originally built using techniques using temperature control techniques that were innovative or standard for the time period in which they were built. Many were built when it was necessary for buildings to have large windows for natural light although now it is realized that sunlight can cause damage. The alternative to light exhibition halls in early museums would have been candle and oil lamps with their respective deposit of ash on the art and high fire risk. Natural ventilation in buildings affects the efficiency of HVAC systems now but was necessary for the building before HVAC systems existed, which is why it so difficult to retroactively install HVAC systems in historic

[72] Museums & Galleries Queensland, *A Practical Guide for Sustainable Climate Control and Lighting in Museums and Galleries*, 14-19.
[73] Karin Kompatsche, Silke Seuren, Rick Kramer, Jos van Schijndel, and Henk Schellen, "Energy efficient HVAC control in historical buildings: a case study for the Amsterdam Museum," *Energy Procedia* 132 (2017): 892-896.
[74] Ferdyn-Grygierek and Grygierek, "HVAC Control Methods for Drastically Improved Hygrothermal Museum Microclimates in Warm Season," 90–91.

museums[75]. This was seen in libraries and the National Gallery in London during the industrial revolution. Soot and other deposits were left from burning coal in lamps and smog. Museums built in more ventilation to remove the toxins and pollutants. At a more localized level, the National Gallery started to glaze their paintings. In 1893, the Gallery encased especially vulnerable paintings in sealed cases to create a microclimate. One of the enclosed paintings was by J. M. W. Turner, an eighteenth-century English painter. The painting remained in better condition compared to the other paintings in the gallery, however, it is unknown if it will deteriorate once removed from the microclimate. Microclimates might lower HVAC use by reducing the need for global humidity control in the museum as the objects most vulnerable to humidity changes are not exposed to them in the microclimate[76]. However, once sealed in a microclimate, it is difficult to remove objects without exposing them to a rapid change of conditions. Museum professionals are divided on the issue as not enough research has been done on the long-term effects[77].

Studies have shown that allowing small seasonal temperature fluctuations can decrease energy demand[78]. For example, the Dutch Archival Legislation approved a bill that allows small short-term fluctuations and the perimeters 18 ± 2 °C/55 ± 5% in 1995 but there have been no revisions to their guideline since. The set-points require a large amount of energy to maintain but can be lowered by allowing the fluctuations proposed by the bill. A museum in The Hague, Netherlands measured intermittent conditions and turned off its air handling unit during weekends when the museum was closed and staff was not present so the tests did not take their

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[75] Eibl and Burmester, "Learning from history. Historic indoor climate conditions and climate control strategies," 217-232.
[76] Shiner, "Trends in microclimate control of museum display cases," 267-271.
[77] Museums & Galleries Queensland, *A Practical Guide for Sustainable Climate Control and Lighting in Museums and Galleries*, 13.
[78] Kompatsche et al., "Energy efficient HVAC control in historical buildings: a case study for the Amsterdam Museum," 892-896.

presence into account. When the unit was off, the conditions moved from the set-points and the HVAC had to make constant adjustments to the temperature. Applying ASHRAE regulations over the Dutch Archival set-points reduced energy demands. Using class A would reduce the energy use by 93%. The collection was primarily paper. They found that changing the indoor climate in this degree did not affect mold degradation[79].

There is little research on whether air control strategies actually work. The current controls do not take into account visitors or crowds and how they affect internal temperature. It is believed that keeping strict constant temperature and relative humidity will reduce risks for objects although the cost to maintain the set-point is not energy efficient. The Amsterdam Museum is housed in a fifteenth-century building. By switching from current set-points to the strictest ASHRAE climate class the museum saved 50% energy in-situ. The Regentenkamer room was preserved from the original building. The museum installed an all-air HVAC and the room has a separate air handling unit. The HVAC recirculates 10% fresh air in the building when the museum is open and does full recirculation when closed. The case study ran several simulations to measure the effectiveness of different strategies for climate control using thermal comfort, energy savings, and risk assessment as primary data points. In the first scenario, energy demand decreased but visitor discomfort increased, especially in winter months. In Climate classes C and D, results showed an increased risk to the paintings. Seasonal adjustments improved the demand for heating and cooling on the system. When considering conditions and comfort level during opening hours into consideration, the ASHRAE controls save more energy

[79] Kompatscher, K., R.P. Kramer, B. Ankersmit, and H.L. Schellen, "Intermittent Conditioning of Library Archives: Microclimate Analysis and Energy Impact," *Building and Environment* 147 (January 1, 2019): 54–60, https://www.sciencedirect.com/science/article/pii/S0360132318306310 (accessed February 12, 2019).

than the adaptive temperature guidelines levels[80]. The interest in the environment's impact on cultural heritage resulted in many publications on safe conditions for collections. Many have very strict rules about what the allowed conditions should be and often are restricted by human comfort and not the collections. As shown in the previous chapters, consideration to how the HVAC system will affect the building is often ignored until it is too late and damage has been done to the museum. This especially is a problem in museums housed in buildings with historic wall treatments such as panels and murals, which are often the first structure to be noticeably damaged in a gallery and signify a larger issue with the HVAC system[81]. The target set-points themselves are based on the limitations of the HVAC system and the building envelope. The strict guidelines cannot be matched by most modern HVAC and use large energy amounts when they can. In some cases, unheated buildings will even have more stable climates than heated ones although the set-points will not be reached[82]. During the 1960's a lot of progress was made in the study of collection conservation and museum indoor climate control. Theories emerged about planned conservation and environmental restoration including an emphasis on the context of artifacts and preservation. During this time the International Council of Museums (ICOM) and the International Centre for the Study of Preservation and Restoration of Cultural Property (ICCROM) came into being to create and enforce guidelines for museums. The studies were done out of necessity after natural disasters threatened many European museums[83].

This relates to the current need to protect collections as environmental change brings more natural disasters. Climate research by the Intergovernmental Panel on Climate Change has

[80] Kompatsche et al., "Energy efficient HVAC control in historical buildings: a case study for the Amsterdam Museum," 892-896.
[81] Vesna Zivkovic and Veljko Dzikic, "Return to basics - Environmental management for museum collections and historic houses," *Energy and Buildings* 95 (2015): 117.
[82] Entradas Silva et al., "A sequential process to assess and optimize the indoor climate in museums," 21-34.
[83] Elena Lucchi, "Multidisciplinary risk-based analysis for supporting the decision making process on conservation, energy efficiency, and human comfort in museum buildings," *Journal of Cultural Heritage* 22 (2016): 1079-1080.

linked incidences of extreme weather to climate change and warns that heat waves, droughts, floods, and storms will increase[84]. The prevalence of increased disaster varies between different parts of the world. Countries in Asia and Africa have higher rates of natural hazards than Europe or North America. Asia is 25 times more likely to have a natural disaster than Europe and North America.[85] In Europe, it is predicted that in temperatures will continue to increase in the period of 2018-2022 following the summer heatwave of 2018[86]. The Paris Agreement urges that more research should be done on observing climate trends and on early warning systems. The agreement hopes to promote technology transfer among nations. If museums adopt and embrace a similar approach, they may be able to help protect cultural heritage at other museums while benefiting from new knowledge[87].

The impacts are first felt by local communities who have to deal with the direct aftermath[88]. Communities are more likely to respond to disasters than to climate change as the results from catastrophes are immediate. Museums need to make decisions to lower energy expenditure as the public and governments will not necessarily respond to long-term planning[89]. For example in a case study in Queensland, Australia, market prices on coastal homes were used to measure the public response to two climate-related events, cyclones and beach erosion. While

[84] Daniel A. Chapman, and Brian Lickel, "Climate Change and Disasters: How Framing Affects Justifications for Giving or Withholding Aid to Disaster Victims," *Social Psychological and Personality Science* 7, 1 (January 2016): 13.

[85]Seidler et al., "Progress on Integrating Climate Change Adaptation and Disaster Risk Reduction for Sustainable Development Pathways in South Asia: Evidence from Six Research Projects," 92.

[86] Moazami, et al., "Impacts of Future Weather Data Typology on Building Energy Performance," 698.

[87] Sophie Pascoe, Shannon Brincat, and Ashleigh Croucher, "The Discourses of Climate Change Science: Scientific Reporting, Climate Negotiations and the Case of Papua New Guinea," *Global Environmental Change* 54 (January 1, 2019): 83, https://www.sciencedirect.com/science/article/pii/S0959378018306551 (accessed March 28, 2019).

[88] Seidler et al., "Progress on Integrating Climate Change Adaptation and Disaster Risk Reduction for Sustainable Development Pathways in South Asia: Evidence from Six Research Projects," 96.

[89] Walter Hein, Clevo Wilson, Boon Lee, Darshana Rajapaksa, Hans de Moel, Wasantha Athukorala, and Shunsuke Managi, "Climate Change and Natural Disasters: Government Mitigation Activities and Public Property Demand Response," *Land Use Policy* 82 (March 1, 2019): 436, https://www.sciencedirect.com/science/article/abs/pii/S0264837718312638 (accessed March 28, 2019).

the increase of potential storms did elicit a response from home buyers, prices for homes only decreased after a cyclone had already happened and potential beach erosion did not affect market prices at all[90].

Cultural heritage promotes a stable community and sense of belonging for its members. Promoting the protection of fragile artifacts in light of their sensitivity to climate change and the related climate events to the public is a vital step museums can take to gain support on securing their collections through building changes[91]. Many of the objects are already at risk and the danger of increased natural disasters should be compared to the already existing threats[92]. Most research on climate risk has been done on archeological sites and not museums or buildings. However, movable objects are still at risk and can be destroyed in sudden disasters such as wildfires or floods and their loss devastating to the affected communities[93]. According to current 100-year and 500-year floodplain data by the Federal Emergency Management Agency (FEMA), more frequent flooding has occurred in the eastern United States than anticipated. Increased temperature would also cost the museum more in the summer in cooling cost[94]. Some factors are outside of the museum's control. The location of the museum building in relation to other buildings, trees, and elevation directly affects the preservation of the collection[95]. Most museums cannot permanently move their entire collection and building to locations that would be less susceptible to climate-related damage due to cost.

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[90] Hein et al., "Climate Change and Natural Disasters: Government Mitigation Activities and Public Property Demand Response", 437-442.
[91] Forino, MacKee, and von Meding, "A Proposed Assessment Index for Climate Change-Related Risk for Cultural Heritage Protection in Newcastle (Australia)," 236.
[92] Forino, MacKee, and von Meding, "A Proposed Assessment Index for Climate Change-Related Risk for Cultural Heritage Protection in Newcastle (Australia)," 246.
[93] Mazurczyk et al., "American Archives and Climate Change: Risks and Adaptation," 112.
[94] Mazurczyk et al., "American Archives and Climate Change: Risks and Adaptation," 114-115.
[95] Elena Lucchi, "Simplified assessment method for environmental and energy quality in museum buildings," *Energy and Buildings* 117 (2016): 219.

There are unfortunately still limitations on how much energy consumption a museum can cut. Certain objects cannot be left completely unprotected from seasonal fluctuations and going against the currently established practices has not been heavily studied. Museums continue to use a high amount of energy as a result. Even in 2013, museums did not consider energy use a priority and the Arts Council England (ACE) found that museum projects used more energy than any other cultural projects[96]. There is currently mounting pressure to decrease carbon emissions in both the public and private sectors. More countries are acknowledging that urban expansion and fossil fuels are directly affecting the environment and attributing to climate change[97]. Museums will soon face external pressure to reduce carbon footprints as more countries are adopting restrictions on energy use and pollution. Such restrictions should not be the driver for change. Museums are responsible for promoting sustainability through education and their own energy usage[98]. As cultural institutions, museums represent their communities whether that means a small historic house with a few patrons or a global recognized museum with thousands of visitors weekly. It is the museum's job to best serve community. Reducing energy usage is beneficial by setting an example for visitors and other museums. By not sticking to the current systems it increases the discovery new methods and systems that are more efficient. Museums can build strong global relationship by sharing information on reducing carbon emissions. Small underfunded museums that currently cannot afford HVAC systems will also benefit and can contribute to lowering energy costs for bigger museums by sharing their past solutions. Energy

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[96] Sharif-Askari and Abu-Hijleh, "Review of museums' indoor environment conditions studies and guidelines and their impact on the museums' artifacts and energy consumption," 191-193.
[97] Karolidis, "The use of underground structures as a solution towards sustainable museums in the Mediterranean basin," 179-180.
[98] Izabela Luiza Pop, and Anca Borza, "SUSTAINABLE MUSEUMS FOR SUSTAINABLE DEVELOPMENT," *Advances In Business-Related Scientific Research Journal* 6, 2 (2015): 121-128.

efficiency also lowers costs for museums[99]. This is important as museums have seen a decrease in public funding[100]

Stable indoor climate preserves not only the collection but the building as well. Not having a working HVAC system can damage the building[101]. Controlling only temperature does not reduce fluctuations in relative humidity. The museum must also be conscious of the historic conditions in the museum. Objects can become accustomed to seasonal fluctuations[102]. Modern buildings do not have fewer problems with maintaining temperature than historic buildings. However, it is difficult to compare because HVAC systems are usually limited and outdated in historic buildings. The value of the building discourages structural changes that would make the system more efficient. Enforcing strict guidelines also does not improve objects that have been in the building for decades[103]. The strict guidelines put pressure on the building as the indoor and outdoor temperatures differ. Wood and brick walls will maintain moisture, so strict guidelines will not ensure an instantaneous change. The informal standard is that no condensation should appear on the window and that the official standard of 50% RH is too high during the heating seasons in this regard. A simple solution would be to set the heating and cooling to turn on and off based on relative humidity instead of temperature[104].

There is little scientific evidence for why the current standards are set how they are. The rationale is primarily based on specific situations and best guesses. Often the research was only

[99] "Perfecting the art of energy efficiency," 6.
[100] Laura Di, Pietro Mugion, Roberta Guglielmetti, Renzi Maria Francesca, and Toni Martina, "An Audience-Centric Approach for Museums Sustainability," *Sustainability* 6, 9 (2014): 5747, https://www.mdpi.com/journal/sustainability (accessed June 20, 2018).
[101] Kramer, van Schijndel, and Schellen, "Dynamic Setpoint Control for Museum Indoor Climate Conditioning Integrating Collection and Comfort Requirements: Development and Energy Impact for Europe," 14.
[102] Ferdyn-Grygierek and Grygierek, "HVAC Control Methods for Drastically Improved Hygrothermal Museum Microclimates in Warm Season," 90–99.
[103] Huijbregts, et al., "A proposed method to assess the damage risk of future climate change to museum objects in historic buildings," 44-48.
[104] Rose, "Effects of climate control on the museum building envelope."

applicable to certain materials and objects but applied to other objects not tested in the studies as law. HVAC systems created indoor conditions not possible before, including RH much lower than the building would have experienced. Past recommended temperatures were lower than today due to capacity of heating systems. The temperature also needs to be within the human comfort zone due to exhibits being open to the public furthering the reason why the system was set at the current point[105]. A further problem is that a large portion of the few studies conducted have all focused on European and Western museums, specifically ones in large cities.

[105] Erhardt, Tumosa, and Mecklenburg, "Applying science to the question of museum climate," 11-15.

A Case Study of Qin Shihuang's Terracotta Army in China

Qin Shihuang's Mausoleum and Museum opened in 1979 in Xi'an city in the Shaanxi province of China. It is known for housing China's famous Terracotta Army, a collection of Terracotta statutes found in Emperor Qin's burial site. The mausoleum is listed as a United Nations Educational, Scientific and Cultural Organization (UNESCO) historic site[106]. The site is unique as the museum also is an active archeological site. Visitors can walk around in an exhibition hall that surrounds the funerary pit where the statutes are on display. Archeologists will also work in the pit. The exhibition hall is at ground level while the pit is subterranean. Those artifacts housed in the museum are well preserved but those artifacts that are unearthed are not. Recently unearthed artifacts have completely different climate needs from both objects that have been in the museum for a long time and visitor comfort levels. HVAC systems are not currently set to these levels and due to financial and technical reasons, the needs of unearthed artifacts are often unmet or ignored[107].

HVAC systems that run 24/7 use a lot of energy which the Qin Shihuang's Museum was trying to avoid. The museum tried different methods in different combinations to improve air quality. The first method, A, was just air conditioning. Two units with 16200w capacity were turned on with the primary function of providing comfort to visitors. The second approach B, placed an air curtain separating the funerary pit and visitor's area. Air curtains are filtered air that is cooled or heated by an air handling unit and returned to a small space to form an air curtain. In C, capillary radiant panels made from polypropylene capillary tubes were fixed into the walls

[106] "Emperor Qinshihuang's Mausoleum Site Museum", accessed April 30, 2019, http://www.bmy.com.cn/2015new/bmyweb/.

[107] Xilian Luo, Zhaolin Gu, Chuck Wah Yu, Ku Li, and Bo Xiao, "Preservation of in situ artefacts by local heating in earthen pit in archaeology museum in cold winter," *Building and Environment* 99 (2016): 29-43, https://www.sciencedirect.com/science/article/pii/S0360132316300154 (accessed December 20, 2018).

and the area was heated or cooled locally. All three methods were then combined into different scenarios 1 through 5.

In scenario 1 temperature was governed solely by the outside climate and the museum experienced a lot of fluctuation throughout the day. The visitor's area being on ground level had greater fluctuations than the funerary pit. The observed fluctuations ranged from 2.7 C to 4.9 C, almost four times the recommended 1.5 C. The temperatures also became very cold and artifacts in the pit became frozen. Relative humidity was also very high as there were exposed soil walls. As a result, heating systems would be beneficial in this scenario due to extreme temperature fluctuations. Air velocity or the rate of air motion in the area remained low in this case. This is good because high air velocity can mean new pollutants are being introduced to an area. The velocity was almost zero during the day but increased at night as the temperature in the pit became closer to the temperature of the rest of the museum. The falling temperatures in the museum caused air to sink while the slightly warmer air from the pit rose.

In scenario 2 just method A, or air conditioning, was used. This stabilized the temperature to 1.0C fluctuations and low air velocity. The RH was close to 80%, but despite the stable climate, the artifacts were not well preserved. It was also impractical to use because the funerary pit and the rest of the exhibit could not be controlled separately, which wasted energy by heating the entire hall when air conditioning was not needed.

In scenario 3, method C, the capillary radiant system was turned on. The temperature greatly increased but with large daily fluctuations. Throughout the day fluctuations measured greater than in scenario 1 when no system was in place. The air velocity was also much higher. So the conditions were unstable.

Both air conditioning and the capillary panels (A and C) were switched on for Case 4. Air conditioning provided stable conditions but not individually. The radiant panels did not create a stable environment. When used together, the radiant panels would heat the pit area faster than the visitor area but with higher daily variation than just air conditioning. In this scenario, the temperature and RH were kept in the range of the recommended values. Air Velocity was lower than in Case 3 with only a radiant system. The air conditioning formed a warm air reserve over the lowered area.

During Case 5, methods A and B, air curtains and radiant panels were used. Air conditioning worked but did not operate in an economical fashion. Air curtains replace conditioning. The museum measured fluctuations close to zero degrees and temperatures in the pit area were consistent with standards. The air curtain created higher temperatures within the pit though. The museum also saw a reduction in Air Velocity.

The cases were compared for energy consumption and separated energy use for visitor comfort and object preservation. Having a local environment like in Scenarios 3 and 5 was ideal for the objects but air conditioning was not efficient. A combination of Scenarios 4 and 5 would be best with the HVAC being shut off at night. An air curtain should be used to replace an air conditioning unit. Combining the systems would be more efficient and the museum suggests that they would only need to air condition a small portion of the exhibit[108].

This case study shows that the current indoor climate suggestions for the use of larger central HVAC system will not work in many scenarios. The indoor climate and comfort levels for museums were determined in the early twentieth century in the United States and Western Europe and have not been properly questioned on their validity. Our current standards do not

[108] Luo et al., "Preservation of in situ artefacts by local heating in earthen pit in archaeology museum in cold winter," 29-43.

take into account the different climates or objects in non-European museums and, to a greater extent, non-traditional museums such as Qin Shihuang's Mausoleum and Museum. At the time of the standards creation, the technology for climate control was not as advanced as it is today[109]. Museums should consider these factors when determining their method for climate control. Even when standards are reached it does not mean the objects will be preserved. Museums should begin to look more at individual cases rather than global set-points and at local heating and cooling units that can cut energy use for the museum while still protecting the object.

[109] Legnér, "On the Early History of Museum Environment Control-Nationalmuseum and Gripsholm Castle in Sweden, c. 1866-1932," 125-137.

Chapter 4: On the Current State of Carbon Emissions Control

The set-point standards for temperature and relative humidity in museums can vary from institution to institution but primarily are based on those developed during World War II as the field became more professional and more institutions adopted them. However, the 1960s marked the wide stream implementation of the National Gallery of London's set-points as a standard for museums. Following the War and other national emergencies, museums saw the need to create set internal environments to protect their collections. Museums used climate control systems in the past, but the rise of professionalism in the museum field led museums to create standards for them[110]. Museums understood their role in the education of the general public and not just scholars. Professionalism developed to help museums better serve their purpose and create a standard for the care of objects[111].

The current standards of environmental conditions are primarily based on observations of the National Gallery of London, which aims to keep the environmental conditions close to a constant 58% RH and 17°C. These values were determined from the conditions in the Manod Slate Quarries in Wales, where the gallery stored its art collection during World War II[112]. The temperature was determined simply by measuring the temperature of the caves. However, originally the humidity in the cave was at close to 100% RH so it needed to be lowered. The chosen RH was the average measured from the National Gallery[113]. Museums found that they could not maintain a single temperature point and extended the set-points into a range of 55–75%

[110] Lucchi, "Simplified assessment method for environmental and energy quality in museum buildings," 218.
[111] Sharif-Askari and Abu-Hijleh, "Review of museums' indoor environment conditions studies and guidelines and their impact on the museums' artifacts and energy consumption," 186.
[112] Eibl and Burmester, "Learning from history. Historic indoor climate conditions and climate control strategies," 218.
[113] Erhardt, Tumosa, and Mecklenburg, "Applying science to the question of museum climate," 11-12.

RH and 12 and 18°C[114]. Thanks to advances in building design and air conditioning, museums could more easily match the set-point parameters allowing more museums to adopt them[115]. Standards for museum interior environment also extend to the acceptable light and pollutant levels[116]. Lighting, for example, ranges from very sensitive material like watercolors to insensitive materials like ceramics. Different objects can be displayed at different light levels or put onto exhibit for a set amount of time periods to reduce exposure to light. Pollutants can be removed from the museum through air filters. Many museums will install fine particle filters into their HVAC system. The most common and dangerous pollutants including Ozone, Sulphur dioxide, and Nitrogen. Air pollutants are also affected by temperature and RH. For example, the amount of Nitrogen dioxide (N02) in the air is reduced when humidity is high because it reacts with water molecules[117].

Guidelines such as having a continuously running HVAC system that can adapt to seasonal changes and setting the temperature set-points close to the exterior temperatures can help museums achieve the standards more easily. This would improve compliance of museums in climates with extreme temperature changes such as cold climates where temperatures fall drastically but the RH becomes too high during the winter[118]. The interior environment should be kept contained, opening windows for ventilation or cooling will cause high fluctuations in temperature or humidity[119]. Different recommended guidelines can be found in the table below.

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[114] Legnér, "On the Early History of Museum Environment Control-Nationalmuseum and Gripsholm Castle in Sweden, c. 1866-1932", 125-126.

[115] Entradas Silva et al., "A sequential process to assess and optimize the indoor climate in museums," 21-34.

[116] Sharif-Askari and Abu-Hijleh, "Review of museums' indoor environment conditions studies and guidelines and their impact on the museums' artifacts and energy consumption."

[117] Sharif-Askari and Abu-Hijleh, "Review of museums' indoor environment conditions studies and guidelines and their impact on the museums' artifacts and energy consumption," 188, 190, 194.

[118] Sharif-Askari and Abu-Hijleh, "Review of museums' indoor environment conditions studies and guidelines and their impact on the museums' artifacts and energy consumption," 187.

[119] Ferdyn-Grygierek, "Indoor environment quality in the museum building and its effect on heating and cooling demand," 44.

Table 1. Recommended Temperature and Relative Humidity Guidelines by Source

Table 1
Temperature and Relative Humidity Parameters for museums indoor environments.by different standards [3,5,10,11].

	T °C	T (24 h)	T Seasonal	RH %	RH (24 h)	RH Seasonal
AICCM 2014	15C–25C	± 4C	–	45–55%	± 5%	40–60%
UK standard 2012	18C–24C	± 4 °C		50%	± 10%	
ASHRAE AA 2011	15C–25C	± 2 °C	Up 5 °C 5 °C Down	50%	± 5%	No change
ASHRAE A 2011	15C–25C	± 2 °C	Up 5 °C Down 10 °C	50%	± 5%	Up 10% Down 10%
ASHRAE A 2011	15C–25C	± 2 °C	Up 5 °C Down 10 °C	50%	± 10%	No change
ASHRAE B 2011	15C–25C	± 5 °C	Up 10 °C (but not above 30 °C) Down as low as necessary to maintain RH control	50%	± 10%	Up 10% Down 10%
ASHRAE C 2011	Rarely over 30 °C, usually below 25 °C	–	–	Within range 25–75% RH Year round.	–	–
ASHRAE D 2011	–	–	–	Reliably below 75% RH	–	–
HCC (Hot Humid) 2002	22C–28C Daily	–	10% acceptable 20% dangerous 40% Destructive	55% – 70% Daily	–	Not to exceed 70% Not below 40%
HCC (Hot Dry) 2002	22C–28C Daily	–		40%–60% Daily	–	
HCC (Temperate) 2002	14C–24C Daily	–		45%–65% Daily	–	

Source: Hawra Sharif-Askari and Bassam Abu-Hijleh, "Review of museums' indoor environment conditions studies and guidelines and their impact on the museums' artifacts and energy consumption," *Building and Environment* 143 (2018): 187, https://www.sciencedirect.com/science/article/pii/S0360132318304207 (accessed December 20, 2018).

Across different organizations, the recommended temperature and RH remain consistent. There have been changes over time for the ideal ranges, especially humidity, which was lowered from 55% RH to 45%RH. Temperature ranges also expanded so that it was easier and more cost and energy efficient to reach 50% RH[120].

Individual museum set-points are created from a compromise between human comfort and the needs of the collection. Often museums will store many different types of materials in

[120]Sharif-Askari and Abu-Hijleh, "Review of museums' indoor environment conditions studies and guidelines and their impact on the museums' artifacts and energy consumption," 187.

one room so conditions need to be a compromise of all materials, as the ideal conditions of one type of material can vary drastically from another. For example, papers need a very different environment than metals. Interior fluctuations vary in size between museums based on the building envelope. This includes everything from building insulation and the presence of visitors increasing the indoor temperature in small rooms and museums[121]. An example study was conducted at an unnamed museum in Upper Silesia, Poland. The museum had four large exhibition halls that were built in 1929 and house Natural Science specimens, Ethnographic objects, and Paintings. The halls each maintain separate thermal zones. They are uninsulated with concrete exterior walls and double-glazed windows. The museum has a weather-controlled central heating which moves air through radiators with thermostat valves that run from early fall until spring. During the summer, the painting gallery has three fan-coils that can be used to heat or cool the exhibition hall. The set-points for the museum are 20°C and RH above 40%. The study lasted a year. During the summer, the museum ventilated the hall by opening windows with sun protection being provided by internal screens. This did not always control fluctuations in either temperature or relative humidity and was at times uncomfortable for visitors and staff. Using windows for ventilation did not allow for air to be distributed evenly due to the size of the halls. The fan-coils also would create an environment much hotter or cooler than the set-points[122].

The temperature and relative humidity stabilized when the heating system was in operation during the winter season and when visitors were not in the museum. The presence of

[121] Ferdyn-Grygierek, "Monitoring of indoor air parameters in large museum exhibition halls with and without air-conditioning systems," 113-116.
[122] Ferdyn-Grygierek, "Monitoring of indoor air parameters in large museum exhibition halls with and without air-conditioning systems," 113-124.

large groups of visitors caused a rise in temperature and humidity especially in smaller rooms in the museum even when the exhibition hall was air conditioned[123].

The museum environment needs to balance the suitable conditions for storing objects and exhibits. Exhibits have a different set of requirements due to frequent foot traffic and needing to display objects in a way that they are easily viewable. People are often present for longer time periods in exhibition areas than in storage areas so temperatures need to be closer to human comfort levels than in storage areas. Human comfort, like ideal object conditions, is also determined by temperature and humidity, as well as air velocity. The number of people within a space can also contribute to comfort[124]. Temperature and relative humidity fluctuations need to be kept at a minimum. Parameters are put in place from the goal set-points with the understanding that gradients in temperature and humidity are unavoidable as air moves between interior and exterior environments. The compromise between conditions is also based on the mechanical limitations of the HVAC system[125]. Many museums are also reevaluating how their architecture and heating systems accommodate new functions such as classrooms and restaurants in the museum. The level of adherence to the set-points depends greatly on how well the museum is able to heat its building and on the layout of the entire museum complex[126].

There are a few issues with the current standards. The first is that human comfort levels and environmental conditions are mostly based on US and Western European standards[127]. Museums also prioritize visitor comfort when deciding the temperature of galleries and

[123] Ferdyn-Grygierek, "Monitoring of indoor air parameters in large museum exhibition halls with and without air-conditioning systems," 116.
[124] Giuseppe Maino and Umberto Lucia, "A thermodynamic approach to the microclimate environment of museums," *Physica A* 517 (2019): 67, https://www.sciencedirect.com/science/article/pii/S0378437118310641 (accessed December 20, 2018).
[125] Ferdyn-Grygierek, "Indoor environment quality in the museum building and its effect on heating and cooling demand," 32-44.
[126] Lucchi, "Simplified assessment method for environmental and energy quality in museum buildings," 217-219.
[127] Legnér, "On the Early History of Museum Environment Control-Nationalmuseum and Gripsholm Castle in Sweden, c. 1866-1932," 125-126.

exhibits[128]. For example, recently unearthed archaeological objects have requirements outside the range conditions in visitor galleries but may be displayed in those conditions if the museum does not have the technical means to keep the conditions at the proper levels[129]. The set-points of human comfort and object preservation can be vastly different especially during winter and summer months. The current standards are not the proven ideal for objects but a compromise or balance of all the different temperature and relative humidity needs. Storage areas can be held to stricter climate control than in exhibit and visitor areas[130]. Limitations of the HVAC system in place will also limit the levels the museum can maintain[131]. Different climates also make it difficult for some museums to reach the level recommended due to the external environment. HVAC systems can be ineffective in more extreme climates. Museums in cold climates, for example, have trouble maintaining RH values during the winter[132]. Energy effectiveness was also not studied in early museums. As a result, many museum systems have high energy consumption due to systems not being able to effectively reach temperature set-points[133]

There is also a question as to how justifiable keeping a strict target is. The original guidelines based from World War II were not scientifically determined and studies looking at the actual effectiveness of these levels are now being done. It is understood that the main concern is reducing fluctuations and keeping the environment as stable as possible. There are some parameters that should be in place, such as keeping RH below 75% in order to prevent mold but

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[128] Karolidis, "The use of underground structures as a solution towards sustainable museums in the Mediterranean basin," 183.
[129] Luo et al., "Preservation of in situ artefacts by local heating in earthen pit in archaeology museum in cold winter," 29-30
[130] Lucchi, "Multidisciplinary risk-based analysis for supporting the decision making process on conservation, energy efficiency, and human comfort in museum buildings," 1079-1089.
[131] Entradas Silva et al., "A sequential process to assess and optimize the indoor climate in museums", 21-34.
[132] Sharif-Askari and Abu-Hijleh, "Review of museums' indoor environment conditions studies and guidelines and their impact on the museums' artifacts and energy consumption," 187.
[133] Sharif-Askari and Abu-Hijleh, "Review of museums' indoor environment conditions studies and guidelines and their impact on the museums' artifacts and energy consumption," 194.

the strict adherence to a set temperature or RH level may not be required by most museums. Allowing seasonal fluctuations can lower day-to-day temperature and humidity fluctuations due to less strain on the HVAC system and the lower difference between interior and exterior climates. The stability is sufficient to protect the objects. Adaptive management would help museums move forward by accounting for climate uncertainty and adapting as new needs arise[134].

The museum would need to be properly insulated but allowing for slow changes can be done without sacrificing the collection. Small seasonal fluctuations also contribute to better comfort for staff and visitors as human comfort levels are relative to outdoor temperature levels[135]. For example, objects in the Gallery Matica srpska in Novi Sad, Serbia showed no significant damage when the temperatures were allowed to fluctuate and ventilation was controlled by windows. While not recommended in environmental control guidelines, being able to control the museum environment with poor funding was more important to the museum[136]. Making sure that the museum is not overheated or cooled during winter or summer months is also vital especially in systems with no direct humidity control and for museums with only seasonal heating and cooling[137]. In one museum it was shown that, while the temperature was maintained in winter, the air exchange through the windows even while closed caused the relative humidity to drop causing damage in wood and textile objects[138]. Historic buildings, in general, have a building envelope with poor hydrothermal performance and insulation. HVAC

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[134] Zhe Zhao, Guofeng Wang, Jiancheng Chen, Jingyu Wang, and Yue Zhang, "Assessment of Climate Change Adaptation Measures on the Income of Herders in a Pastoral Region," *Journal of Cleaner Production* 208 (January 20, 2019): 729, https://www.sciencedirect.com/science/article/pii/S0959652618331020 (accessed March 28, 2019).

[135] Entradas Silva et al., "A sequential process to assess and optimize the indoor climate in museums," 21-34.

[136] Zivkovic and Dzikic, "Return to basics - Environmental management for museum collections and historic houses."

[137] Ferdyn-Grygierek, "Monitoring of indoor air parameters in large museum exhibition halls with and without air-conditioning systems," 113-116.

[138] Zivkovic and Dzikic, "Return to basics - Environmental management for museum collections and historic houses."

systems will eventually not be able to maintain the proper temperature as heat transfers between the exterior and interior environments[139].

There are benefits to controlling the museum's interior climate with an HVAC system. Despite the success of some museums without an HVAC system, many other museums cannot maintain a stable environment without such technologies in place. Museums can suffer from fluctuations or humidity levels that cannot be controlled by temperature levels[140]. It also mitigates risks of the external temperature suddenly changing to have an HVAC running year-round[141]. Air-conditioning systems are still the primary way to cool a building and will mechanically ventilate the building and reduce pollutants that would be difficult to remove through manual filtration systems[142].

One idea is to have moisture buffering to stabilize relative humidity. This works by positioning the objects in the collection together so that objects can buffer moisture from each other. Objects that can absorb moisture without being damaged are placed in locations where they can lower the Relativity Humidity in the rest of the room[143]. There is also adaptive comfort to confront visitor needs being put before object preservation. The concept is that humans will adapt more quickly to climate changes and as long as temperature remains within human comfort levels, strict guidelines are not needed for visitors as far as humidity and temperature is

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[139] Ferdyn-Grygierek and Grygierek, "HVAC Control Methods for Drastically Improved Hygrothermal Museum Microclimates in Warm Season," 90-91.
[140] Ferdyn-Grygierek, "Indoor environment quality in the museum building and its effect on heating and cooling demand," 32-44.
[141] Ferdyn-Grygierek, "Monitoring of indoor air parameters in large museum exhibition halls with and without air-conditioning systems," 113-116.
[142] Yuchen Shia and Xiaofeng Li, "A study on variation laws of infiltration rate with mechanical ventilation rate in a room," *Building and Environment* 143 (2018), 269-279, https://www.sciencedirect.com/science/article/pii/S0360132318304293 (accessed October 24, 2018).
[143] Ferdyn-Grygierek and Grygierek, "HVAC Control Methods for Drastically Improved Hygrothermal Museum Microclimates in Warm Season," 90-91.

concerned. Under this model, light levels are the primary concern for visitor comfort in the museum[144].

HVAC systems in development can be controlled using sensors instead of user inputted set-points. This allows the system to make constant adjustments based on the number of visitors and the effectiveness of the system. The device will attach to central units and can alert staff of fluctuations and adjust the HVAC in accordance to changes. More advanced versions can even control other building components such as windows or shades to adjust to temperature and RH in addition to the HVAC system[145].

Museums should not be happy staying in the status quo and accepting high costs and energy usage. New technology is constantly being created that the museum can utilize. Standardization is important but it is also important to be critical of using set-points that were created through limited experiences. In reducing our global carbon footprint, energy-effective systems are vital.

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[144] Lucchi, "Multidisciplinary risk-based analysis for supporting the decision making process on conservation, energy efficiency, and human comfort in museum buildings," 1080.

[145] Francesca Stazi, Benedetta Gregorini, Andrea Gianangeli, Gabriele Bernardini, and Enrico Quagliarini, "Design of a Smart System for Indoor Climate Control in Historic Underground Built Environment," *Energy Procedia* 134 (2017): 521-526.

Conclusion

Museums are able to lower carbon emissions, not only for environmental reasons but to help provide protection for objects in museums in which expensive HVACs are not feasible. This becomes vitally important as smaller countries already may not have the same infrastructure or funds for their museums as Western Europe and the United States have. In addition, in regions such as Asia, there is a different culture on temperature comfort and an increase risk of climate change events far greater than in Europe. The standards for museum climate control also focus on the environmental conditions of Europe and are based on individual observations. Trying to adhere to the strict recommended set-points can put a large strain on the museum's resources and building. Even when achieved, museums will observe deterioration in their collection. HVAC systems can, however, improve the conditions in museums but are a recent invention only being widely used in the twenty-first century. Outside of the United States and Western Europe many museums may not have HVAC systems in place. Even within these regions small museums may not be able to afford the expensive systems and rely on other forms of climate control. As more pressure is put on museums from external sources to reduce carbon emissions and energy consumption, museums should reevaluate set-points and systems that lack in scientific evidence and work creating solutions that can be used globally.

Bibliography

Chapman, Daniel A., and Brian Lickel. "Climate Change and Disasters: How Framing Affects Justifications for Giving or Withholding Aid to Disaster Victims." *Social Psychological and Personality Science* 7, 1 (January 2016): 13-20.

Di, Laura, Pietro Mugion, Roberta Guglielmetti, Renzi Maria Francesca, and Toni Martina. "An Audience-Centric Approach for Museums Sustainability." *Sustainability* 6, 9 (2014): 5745-5762. https://www.mdpi.com/journal/sustainability (accessed June 20, 2018).

Eibl, Melanie and Andreas Burmester. "Learning from history. Historic indoor climate conditions and climate control strategies." In *Climate for Collections, Standards and Uncertainties*, edited by Jonathan Ashley-Smith, Andreas Burmester and Melanie Eibl, 217-232. Munich: Archetype Publications Ltd, 2013.

"Emperor Qinshihuang's Mausoleum Site Museum." Accessed April 30, 2019. http://www.bmy.com.cn/2015new/bmyweb/.

Entradas Silva, Hugo, Fernando M.A. Henriques, Telma A.S. Henriques, and Guilherme Coelho. "A sequential process to assess and optimize the indoor climate in museums." *Building and Environment* 104 (2016): 21-34. https://www.sciencedirect.com/science/article/pii/S0360132316301445 (October 24, 2018).

Erhardt, David, Charles S. Tumosa and Marion F. Mecklenburg. "Applying science to the question of museum climate." In *Museum Microclimates Conference,* edited by Tim Padfield and Karen Borchersen, 11-18. Copenhagen: The National Museum of Denmark, 2007.

Ferdyn-Grygierek, Joanna. "Indoor environment quality in the museum building and its effect on heating and cooling demand." *Energy and Buildings* 85 (2014): 32-44.

Ferdyn-Grygierek, Joanna. "Monitoring of indoor air parameters in large museum exhibition halls with and without air-conditioning systems." *Building and Environment* 107 (2016): 113-126. https://www.sciencedirect.com/science/article/pii/S0360132316302797 (accessed October 24, 2018).

Ferdyn-Grygierek, Joanna, and Krzysztof Grygierek. "HVAC Control Methods for Drastically Improved Hygrothermal Museum Microclimates in Warm Season." *Building and Environment* 149 (2019): 90-99. https://www.sciencedirect.com/science/article/pii/S0360132318307546 (accessed December 20, 2018).

Forino, Giuseppe, Jamie MacKee, and Jason von Meding. "A Proposed Assessment Index for Climate Change-Related Risk for Cultural Heritage Protection in Newcastle (Australia)." *International Journal of Disaster Risk Reduction* 19 (October 1, 2016): 235-248. https://www.sciencedirect.com/science/article/pii/S2212420916301078 (accessed March 28, 2019).

Hein, Walter, Clevo Wilson, Boon Lee, Darshana Rajapaksa, Hans de Moel, Wasantha Athukorala, and Shunsuke Managi. "Climate Change and Natural Disasters: Government Mitigation Activities and Public Property Demand Response." *Land Use Policy* 82 (March 1, 2019): 436-443. https://www.sciencedirect.com/science/article/abs/pii/S0264837718312638 (accessed March 28, 2019).

Huijbregts, Z., R.P. Kramer, M.H.J. Martens, A.W.M. van Schijndel, and H.L. Schellen. "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.

Karolidis, Dimitrios. "The use of underground structures as a solution towards sustainable museums in the Mediterranean basin." In *Climate for Collections, Standards and Uncertainties*, edited by Jonathan Ashley-Smith, Andreas Burmester and Melanie Eibl, 179-192. Munich: Archetype Publications Ltd, 2013.

Kompatsche, Karin, Silke Seuren, Rick Kramer, Jos van Schijndel, and Henk Schellen. "Energy efficient HVAC control in historical buildings: a case study for the Amsterdam Museum." *Energy Procedia* 132 (2017): 891-896.

Kompatscher, K., R.P. Kramer, B. Ankersmit, and H.L. Schellen. "Intermittent Conditioning of Library Archives: Microclimate Analysis and Energy Impact." *Building and Environment* 147 (January 1, 2019): 50-66. https://www.sciencedirect.com/science/article/pii/S0360132318306310 (accessed February 12, 2019).

Kramer, Rick, Jos van Schijndel, and Henk Schellen. "Dynamic Setpoint Control for Museum Indoor Climate Conditioning Integrating Collection and Comfort Requirements: Development and Energy Impact for Europe." *Building and Environment* 118 (June 2017): 14-31. https://www.sciencedirect.com/science/article/pii/S0360132317301269 (accessed February 12, 2019).

Legnér, Mattias. "On the Early History of Museum Environment Control-Nationalmuseum and Gripsholm Castle in Sweden, c. 1866-1932." *Studies in Conservation* 56, 2 (2011): 133. http://dx.doi.org/10.1179/sic.2011.56.2.125 (accessed September 25, 2018).

Leskard, Marta. "A sustainable storage solution for the Science Museum Group." *Science Museum Group Journal* 4 (Autumn 2015). http://dx.doi.org/10.15180/150405 (accessed June 20, 2018).

Luo, Xilian, Zhaolin Gu, Chuck Wah Yu, Ku Li, and Bo Xiao. "Preservation of in situ artefacts by local heating in earthen pit in archaeology museum in cold winter." *Building and Environment* 99 (2016): 29-43. https://www.sciencedirect.com/science/article/pii/S0360132316300154 (accessed December 20, 2018).

Lucchi, Elena. "Multidisciplinary risk-based analysis for supporting the decision making process on conservation, energy efficiency, and human comfort in museum buildings." *Journal of Cultural Heritage* 22 (2016): 1079-1089.

Lucchi, Elena. "Simplified assessment method for environmental and energy quality in museum buildings." *Energy and Buildings* 117 (2016): 216-229. https://www.journals.elsevier.com/energy-and-buildings (accessed October 24, 2018).

Maino, Giuseppe, and Umberto Lucia. "A thermodynamic approach to the microclimate environment of museums." *Physica A* 517 (2019):66-72. https://www.sciencedirect.com/science/article/pii/S0378437118310641 (accessed December 20, 2018).

Mazurczyk, T., N. Piekielek, E. Tansey, and B. Goldman. "American Archives and Climate Change: Risks and Adaptation." *Climate Risk Management* 20 (January 1, 2018): 111-125. https://www.sciencedirect.com/science/article/pii/S2212096318300135 (accessed March 28, 2019).

Moazami, Amin, Vahid M. Nik, Salvatore Carlucci, and Stig Geving. "Impacts of Future Weather Data Typology on Building Energy Performance – Investigating Long-Term Patterns of Climate Change and Extreme Weather Conditions." *Applied Energy* 238 (March 15, 2019): 696-720. https://www.sciencedirect.com/science/article/pii/S0306261919300868 (March 28, 2019).

Museums & Galleries Queensland, Museums & Galleries of NSW, Regional and Public Galleries Association of NSW, and Regional Galleries Association of Queensland. *A Practical Guide for Sustainable Climate Control and Lighting in Museums and Galleries*. Sydney: International Conservation Services and Steensen Varming, 2014.

Napp, Margus, and Targo Kalamees. "Energy Use and Indoor Climate of Conservation Heating, Dehumidification and Adaptive Ventilation for the Climate Control of a Mediaeval Church in a Cold Climate." *Energy & Buildings* 108 (December 2015): 61-71.

Neuhaus, Edgar. "A critical look at the use of HVAC systems in the museum environment." In *Climate for Collections, Standards and Uncertainties*, edited by Jonathan Ashley-Smith, Andreas Burmester and Melanie Eibl, 117- 126. Munich: Archetype Publications Ltd, 2013.

Pascoe, Sophie, Shannon Brincat, and Ashleigh Croucher. "The Discourses of Climate Change Science: Scientific Reporting, Climate Negotiations and the Case of Papua New Guinea." *Global Environmental Change* 54 (January 1, 2019): 78-87.https://www.sciencedirect.com/science/article/pii/S0959378018306551 (March 28, 2019).

Perez-Lombard, Luis, Jose Ortiz, and Ismael R. Maestre. "The map of energy flow in HVAC systems." *Applied Energy* 88 (2011): 5020-5031. https://www.sciencedirect.com/science/article/pii/S030626191100448X?via%3Dihub (accessed June 20, 2018).

"Perfecting the art of energy efficiency." *Air Conditioning, Heating & Refrigeration News* 247, 11 (2012): 6-7.

Pop, Izabela Luiza, and Anca Borza. "SUSTAINABLE MUSEUMS FOR SUSTAINABLE DEVELOPMENT." *Advances in Business-Related Scientific Research Journal* 6, 2 (2015): 119-131.

Rose, William. "Effects of Climate Control on the Museum Building Envelope." *Journal of the American Institute for Conservation* 33, 2 (1994): 199-210. https://www.jstor.org/stable/3179428 (accessed September 25, 2018).

Seidler, Reinmar, Katie Dietrich, Sarah Schweizer, Kamaljit S. Bawa, Shashikant Chopde, Farrukh Zaman, Anshu Sharma, Sumana Bhattacharya, Laxmi P. Devkota, and Sarala Khaling."Progress on Integrating Climate Change Adaptation and Disaster Risk Reduction for Sustainable Development Pathways in South Asia: Evidence from Six Research Projects." *International Journal of Disaster Risk Reduction* 31 (October 2018): 92-101. https://www.sciencedirect.com/science/article/pii/S2212420918305223 (accessed March 28, 2019).

Sharif-Askari, Hawra, and Bassam Abu-Hijleh. "Review of museums' indoor environment conditions studies and guidelines and their impact on the museums' artifacts and energy consumption." *Building and Environment* 143 (2018): 187. https://www.sciencedirect.com/science/article/pii/S0360132318304207 (accessed December 20, 2018).

Shia, Yuchen, and Xiaofeng Li. "A study on variation laws of infiltration rate with mechanical ventilation rate in a room." *Building and Environment* 143 (2018): 269-279.

https://www.sciencedirect.com/science/article/pii/S0360132318304293 (accessed October 24, 2018).

Shiner, Jerry. "Trends in microclimate control of museum display cases." In *Museum Microclimates Conference*, edited by Tim Padfield and Karen Borchersen, 267-275. Copenhagen: The National Museum of Denmark, 2007.

Stazi, Francesca, Benedetta Gregorini, Andrea Gianangeli, Gabriele Bernardini, and Enrico Quagliarini. "Design of a Smart System for Indoor Climate Control in Historic Underground Built Environment." *Energy Procedia* 134 (2017): 518-527.

Zhao, Zhe, Guofeng Wang, Jiancheng Chen, Jingyu Wang, and Yue Zhang. "Assessment of Climate Change Adaptation Measures on the Income of Herders in a Pastoral Region." *Journal of Cleaner Production* 208 (January 20, 2019): 728-735. https://www.sciencedirect.com/science/article/pii/S0959652618331020 (accessed March 28, 2019).

Zivkovic, Vesna and Veljko Dzikic. "Return to basics - Environmental management for museum collections and historic houses." *Energy and Buildings* 95 (2015): 116-123.