Mapping and Evaluating the Environmental Conditions and Energy Usage in the Cambridge University Library

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Abstract

This report aims to demonstrate the possibility of executing a flexible set point mechanism for controlling the environmental conditions in the Cambridge University Library. It also presents the necessity of following the new guideline for the storage of archival materials – PD5454:2012. The report further reveals issues related to the sustainable design and cost-effective storage.

Introduction

As the cost of energy soars during the recent years, improving the energy economy has become more strategically important in the sustainable development of a building. According to reports from the Estate Management, the cost of utilities during the past five years has been rising at an alarming rate (Fig.1). Also, in response to the emission target set by the Higher Education Funding Council for England (HEFCE), the University is committed to actions including:

That Scope 1 & 2 emissions attributable to activities which are not associated with scientific and technical research within Departments should seek reductions in absolute emissions of 34% from 2005 levels by 2020, subject to the availability of suitable cost-effective technology and progress towards meeting Government targets for decarbonisation of the grid. – University Carbon Management Plan 2010

In response, the Energy and Carbon Reduction Project (ECRP) is created under the University to help to increase the energy economy of university buildings. As the Cambridge University Library (main building) currently consumes the third largest amount of carbon amongst all the buildings in the University1, it is chosen as a subject of the ECRP’s pilot program. Under the ECRP, the project of this report takes the first step to examine the environment and energy usage of the University Library.

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1 Refer to the University of Cambridge Carbon Management Plan - IHW/MRW/PJH/MRB – 27 September 2010
Figure 1: There has been a steep increase in the cost of utilities during the past five years. The annual cost of utilities in 2020 is forecasted to be reaching £32 million.

Objective

The objective of this project is to explore ways to improve the energy economy of the University Library (main building) without compromising the integrity of the archival materials, through mapping and evaluating the environmental conditions and energy usage of the repositories and the non-repositories.

Background

The original University Library building was designed by Giles Gilbert Scott in 1934. Since then, seven other extensions of the university library have been constructed. This includes the West Bookstacks (1972), the North West Corner, the South West Corner, Aoi Pavilion, Rotherham, Phase 5 Extension and Phase 6 Extension Buildings.

Methodology

The project is carried out in four stages:

1. Classification: Define the repository areas in the University Library and Study the recommended environmental conditions based on the British Standards
2. Conditions: Assess the current environmental conditions and energy usage in the University Library
3. Measurement: Measure the real-time data of the temperature and humidity conditions in the University Library
4. Recommendation: Identify the sustainability issues in the University Library and Propose viable solutions

It is worth noticing that the actual project is carried out in less than four weeks. Under such tight schedule, all four stages have been investigated concurrently. The author would like to apologize in advance for any imprudence in the collection, presentation and analysis of data in this report.

Results

Defining the Repositories

Two definitions of a repository given by the British Standards Institute are listed below:

Repository – building, part of a building, or area(s) within a building designated for the long-term storage of documents (3.29, PD5454:2012²)

Repository – building, part of a building, or area within a building designated for the storage of documents and constructed and maintained to minimize the risk of damage, decay and unauthorized access and to furnish proper conditions of custody (3.23, BS5454:2012³)

However, it is difficult to directly apply such definition onto the storage spaces in the Library. All of the documents in the Library are stored for long-term preservation; yet many of them are subject to transfer, away from the Library or to the reading rooms. Also, a significant number of collections are stored in the reading rooms and open-access spaces such as the corridors throughout the buildings, making it difficult to apply the official definitions (old or new) to classifying repositories in the University Library.

Upon a detailed discussion with Dr. Jill Whitelock, the Head of Special Collections at the University Library, a modified definition of a repository is presented below:

A repository is defined as a closed-access room storing one or more of the following four types of documents:

- Manuscripts
- Pre-1900 Printed Materials (Rare Books)
- Post-1899 Printed Materials (Modern Books)
- Microforms

Currently, documents stored in the Library are categorized into the four types of documents as listed above. Specifying the types of storage materials in a repository helps to identify the repositories in the Library, easily excluding rooms for other usage such as equipment storage rooms, office, exhibition space etc. Also, as opposed to the generalized definition of “area(s)

within a building designated for … storage” listed in PD5454 (or similar one in BS5454), the modified definition specifies a repository to be a closed access room. Such specificity helps to exclude publicly accessible areas such as the reading rooms (which also serve as a storage space) into the classification of repositories in this project.

The Guideline – BS/PD5454

While defining the repository areas in the Library for the subsequent investigation, one inevitably has to deal with the choice between following the old (BS5454:2000) and the new guideline (PD5454:2012). The British Standard (BS) 5454 was published in the year 2000 but was formally withdrawn in March 31st, 2012. It has been replaced by the new guideline, the Published Document (PD) 5454. Even though the old guideline has been withdrawn, most of the archives around UK continue to follow it.

One reason is because most of the existing archives are built and maintained after BS5454 for more than a decade. Switching from following one standard to another seems to result in unnecessary amount of work and lead to unforeseen consequences.

Another reason is that, the new standard has a limited lifespan of around three years before the publishing of a new Europe-wide standard or its own upgrading to a British Standard. The sentiment around most UK archives is that making the changes to follow the new guideline seems to be a potentially extraneous effort if the Europe-wide standard is adapted. Between keeping the status quo and following a new guideline that faces the possibility of being replaced in the future, the existing archives choose the former.

On the other hand, PD5454 is more up-to-date, detailed and carries the results from the recent decade of research on archive preservation. Almost every section listed originally in BS5454 has been expanded and made more specific. In the context of the environmental setting, the author of this report believes that the Cambridge University Library should formally take the storage environment guidelines in PD5454 into consideration. This is because the Recommended Environmental Criteria listed in the new Published Document provides a detailed set of reference for the archives to realistically assess and control their storage environment and other venues such as the reading rooms and exhibition spaces. Also, it presents a new approach that considers energy economy into archival storage.

To show that the Recommended Environmental Criteria for storage environment listed in PD5454 is more practical for the University Library than that listed in BS5454, a table of comparison is presented as following.

\[\text{Table of Comparison}\]

Note: PD5454 does not carry as high a status and authority as BS5454, as defined by the British Standards Institute. Yet, it should be noted that both BS5454 and PD5454 only carry the role of a guideline or recommendation and are not legal-binding.
The criteria for temperature and humidity conditions listed in PD5454 are categorized based on the type of materials as opposed to the frequency of handling used in BS5454. Currently, there is no historical record of the frequency of handling of the archival materials in the University Library. Instead, the Library has four major types of materials as shown in the previous section: Manuscripts, Pre-1900 Printed Materials, Post-1899 Printed Materials and Microforms. This clearly fits into the categories listed in the PD5454, which are:

1. Mixed Archives
2. Paper Record Storage
3. Photographic, Audio, Visual & Electronic Media (Cool Storage)
4. Photographic, Audio, Visual & Electronic Media (Cold Storage)

Also, manuscripts, rare books and microforms are usually stored together in many rooms in the Library, making any kind of categorization difficult. Yet, the new categorized “Mixed Archives” in the PD5454 presents a set of realistic environmental criteria that can be directly applied to many storages rooms in the Library. The Published Document states that the ranges of temperature and relative humidity for the Mixed Archives “are recommended as a mean of preventing even sensitive archival materials … from being compromised when stored alongside less critically sensitive archival material.” This clause has considered the realistic situation in the archives that many types of materials are stored together and would require an unrealistic amount of effort to assort each specific type of material for a corresponding repository. The all-encompassing solution in the PD5454 lists out broader ranges of temperature and relative humidity criteria for the Mixed Archives than those listed in the BS5454. Therefore, the PD5454 presents a realistic set of environmental criteria for the storage environment in the Library which BS5454 is unable to achieve.

\[ ^7 \text{Ibid. (3) Section 7.3.1, 7.3.2, 7.3.3} \]
\[ ^8 \text{Ibid. (2) Section 4.2.2, 4.2.3, 4.3.2, 4.3.3} \]
\[ ^9 \text{Ibid. (7)} \]
\[ ^10 \text{Ibid.(8)} \]
\[ ^11 \text{Ibid. (3) Section 7.5.3} \]
\[ ^12 \text{Ibid. (2) Section 4.7.2} \]
\[ ^13 \text{This category is not applicable to the Library as it does not have a cold storage, which is defined in PD5454 as a storage environment kept at a temperature range of } -15^\circ C \pm 5^\circ C. \]
\[ ^14 \text{Ibid. (2) 4.2.2} \]
In the context of environmental control, the most crucial change made in the PD5454 with respect to the BS5454 is the allowance of flexibility in the environmental management. “Instead of a tight level of stability and control” based on the set points for temperature and relative humidity, the new guideline allows “environmental fluctuations to occur with seasonal change”, making “an emphasis on low energy solutions.”\textsuperscript{15} In the BS5454, it states that the storage temperature and relative humidity “should be at a fixed point” within the range and tolerance as shown in Table 1.\textsuperscript{16} This means that the storage temperatures and relative humidity will have to strictly follow a fixed set of values throughout the year. This will result in unnecessarily large amount of electricity and gas consumption for cooling in the summers and for heating in the winters.

Therefore, the author of this report proposes a \textit{flexible set point mechanism} for the environmental control in the Cambridge University Library based on seasonal changes:

\begin{itemize}
\item Step 1: Gradually increase the set temperature by 2\(^\circ\)C across a 10-week period (Spring)
\item Step 2: Stabilize over the next 10-12 weeks (Summer)
\item Step 3: Gradually decrease the set temperature by 2\(^\circ\)C across a 10-week period (Autumn)
\item Step 4: Stabilize over the next 10-12 weeks (Winter)
\end{itemize}

The change in temperatures can be achieved by the Building Management System (BMS). The BMS currently controls all the air-handling units (AHUs) and a number of reheat in the Library. By changing the temperature set point of each individual AHU or re heater according to the \textit{flexible set point mechanism} described above, the designated room environment can be controlled to increase energy savings.

The value 2\(^\circ\)C is tentatively chosen such that a two-degree deviation from the current temperature set points of the repositories in the University Library (15-17.5\(^\circ\)C) will not exceed the recommended temperature range for Mixed Archives in PD5454.\textsuperscript{17}

To calculate the benefit of the \textit{flexible set point mechanism} in terms of energy savings, a rudimentary model is employed (as shown in Appendix I). Taking into account of only the repositories and the reading rooms, a conservative estimate of the \textit{annual energy saving} is £23,407 (assuming 9 pence/kwh). Such energy saving is substantial, as it accounts about 7.1 percent of the cost of electricity in 2011.\textsuperscript{18} As only computer command changes on the BMS are needed to execute the \textit{flexible set point mechanism}, it is rather cost-effective.

The author of this report believes that the rudimentary model aims only to demonstrate the possibility of an energy saving through the mechanism. The actual figure can be much larger because the model does not include the electricity consumed in humidifying and transporting air, which takes up a large proportion of the total energy consumption of the Library. Calculation of the energy savings in air humidification and transportation can only be done under a much more complicated model. Therefore, assessing the full benefits of the \textit{flexible
set point mechanism requires a more detailed and professional approach which is beyond the scope of this project.

Further Remarks on the Flexible Set Point Mechanism

Optimizing versus Stabilizing

Currently, the University Library’s approach to archival preservation is to avoid changes. This means avoiding the movement of valuable manuscripts and rare books and avoiding large fluctuations in the environmental conditions. The rationale behind such approach is that since most of the books have been kept well in the past environmental conditions (fixed set points), it is best not to move them or change the external settings to avoid any unforeseen damage which can be irreversible for valuable materials.

However, upon careful examination, such rationale is not as sound. First, currently rare books and manuscripts in the University Library are not acclimatized upon moving between the repositories and the reading rooms. Not only there is a difference in the environmental conditions between the repositories and the reading rooms, but also there is an additional change in environment between the corridor/staircase and the aforementioned locations. As each borrowed reference material is moved from the repository through the corridor to the reading room and back, it experiences 4 changes in external environment throughout the process. Even though the frequency of movement per document throughout a year is expected to be low, the number of changes in conditions one document has to experience each time it is borrowed is not negligible. This suggests that the movement of documents in a repository and the environmental changes the documents experience are unavoidable. Hence, the ground of maintaining stability for the archival materials is not sound.

Also, a fixed set of environmental set points does not imply an absolutely stable environment. Currently, repositories’ environment in the Library is controlled under the Building Management System with fixed environmental set points throughout the year. However, regardless of what repository, old or new, airtight or not, the temperature fluctuates at least 0.2°C daily. According to the plan set out in the flexible set point mechanism, the temperature of a repository increases only 0.2°C per week. This is comparable to the larger-than-0.2°C temperature fluctuation in a regular repository of the Library. Considering that documents stored in the repositories remain intact under such daily fluctuation, it is unlikely that these documents will experience any damage from the change in temperature setting given the rate of change is comparable to the minimum daily fluctuation. Therefore, the difference between optimizing and stabilizing a repository is minimal when the change in temperature set point comes down to the scale of the daily temperature fluctuation.

Will the change in temperature damage the materials?

The thermal response time of collection items varies from minutes to hours...If major temperature changes are necessary for operational reasons, such as seasonal energy savings, the period of adjustment should be spread over a period several times longer than the slowest response time of collection items. (PAS198:2012)  

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19 Refer to Appendix for a specific example
According to PAS198 published by the British Standards Institute, the rate of change in temperature set point has to be several times longer than the slowest response time of collection items to avoid damage to the archival materials. In an effort of demonstrating the feasibility of the temperature change in the flexible set point mechanism, a simple model is used to estimate the range of thermal response time of an unpacked document. (That is, the document is not boxed or sealed so as to be protected in a microenvironment, as the protected ones generally do not fluctuate much with external environmental changes hence not considered in this case.)

As shown in Appendix II, the response time of the paper documents in the four scenarios with respect to a 2°C external temperature rise, whether small or large, leather-covered or not, is at most two hours. As the external temperature set point only increases by 2°C every 10 weeks, it is much longer than the thermal response time of a shelf of books. However, there may be other collection items with slower response time. Still, based on the result from the model and the statement from PAS198 that “the thermal response time of collection items varies from minutes to hours”, it can be predicted with confidence that the change in temperature set points according to the flexible set point mechanism will not result in any damage in the material.

It is worth noticing that this mechanism is proposed to demonstrate the feasibility and the possible benefits of utilizing flexible environmental set points. Currently, it includes only a plan of changing the temperature set points. How relative humidity set points should be adjusted to maximize the energy savings requires a much more complicated analysis which is beyond the scope of this project. However, it is speculated that the current change in temperature set points has a less than visible impact on the relative humidity of the room environment. This is because the humidity change in a room in response to the gradual and incremental temperature change is distributed over a long period of time and will likely be absorbed by the contents in the room.

Assessing the Current Environmental Conditions

Currently, the environmental conditions in the University Library is monitored by the Building Management System (BMS), a computer-based control system that aims to control, monitor and optimize the performance of the heating, cooling, humidification, ventilation and various other service systems in the library buildings.

The BMS allows the personnel-in-charge to remotely control and monitor the environmental settings in most of the repositories. The system itself is convenient, easy to use and covers a broad range of rooms in the Library. However, it also has several issues.

Short Memory Space for the Study of Historical Data

First, the BMS possesses a short memory space for monitored environmental data, which makes studying the history of environmental conditions in the Library difficult. Currently, the monitored data are stored for usually a week as there are little incentives to use the data. However, considering that the guideline for the storage of archival materials changes every decade, the requirements on the environmental settings in the repositories and reading rooms change. Without a proper understanding of the historical data, the Library will find it difficult to take the initiative to change according to any new guideline.
At the moment, the University Library is following the old guideline BS5454 as opposed to the new PD5454 under a conservative rationale. This occurs in part because the Library does not have a thorough understanding of its history of environmental conditions and hence the confidence to make change based on the new guideline. As a leader of the archives in the UK, the Cambridge University Library should take initiative in actively managing and studying its history of environmental conditions. As the demand for energy savings rises during the recent years, a thorough understanding of its environmental history becomes particularly important for the Library to consider the energy impact of its effort on preservation and conservation of archival collections. Hence, there will be a growing need for the BMS to record the history of the carbon intensive buildings/repositories in the Library. Logging the data for a long period of time is currently a viable option for the BMS and should be utilized.

Lack of Recalibration for the Past Decade

The BMS, since its installation, has not been recalibrated for the past decade. Even though the monitors of the BMS in the Library are constructed to provide a certain level of accuracy for a long period of time, their accuracy can be affected due to wear and tear or external influence such as dust and moisture. The demand on a higher level of accuracy on the monitors grows especially when considering actions such as the flexible set point mechanism, which concerns incremental changes detectable only under accurate monitoring.

The lack of recalibration of the BMS also inspires the subsequent real-time measurement in this project, which aims to study any discrepancy between the monitored data on the BMS and the realistic conditions. Because of the short memory space of the BMS, it was not feasible to study the extent of how much the BMS data conforms to the environmental design criteria suggested by BS5454 or PD5454. Instead, after surveying across the BMS data, it is found that the monitored data are generally within the requirement of the guidelines. However, the extent of conformity of the data to the guideline cannot be calculated due to complexity of the analysis required.

Assessing the Current Energy Usage

Currently, the energy usage of the University Library buildings is tracked by the Workplace Footprint Tracker, available on the Energy Dash Board, a website still in its final testing stage. The University Library is divided into twelve zones for metering. Out of the twelve zones, seven of them have their cooling and ventilation energy consumption monitored, while the other five have either cooling or ventilation energy consumption metered. The reason for such difference is because cooling and ventilation systems are both available only in the seven zones, as the buildings where they situate have higher environmental criteria.

As the Workplace Footprint Tracker (WPFT) is still a prototype, this project aims mainly not to utilize its data but to reveal the various issues encountered while using the program.

Discrepancy between WPFT Diagrams

21 The 12 zones include: Aoi, Exhibition Room, Kitchen, Locker Room, North and South Courts, North and South West Corner, West Bookstacks (WB) Basement, WB North, WB South, West Bookstacks (1972). The plug load in the Kitchen is also metered.
On the Workplace Footprint Tracker, there is an option to reveal the summary diagram of the University Library energy consumption (Fig. 2). Also, there is another option to reveal the diagram of the Total Climate Energy Consumption in the Library, which refers to the energy used by the cooling and ventilation systems (Fig. 3). Yet, the difference between those two diagrams is not clear. Both diagrams chronicle the electricity usage through October 2011 to August 2012.

As shown in Figure 4, which compares the two diagrams aforementioned, the University Library Energy Consumption is very close to the Total Climate Energy Consumption from October 2011 to April 2012. Yet, the difference between the two graphs grows and intensifies from May to August 2012. In fact, in August 2012, the University Library Energy Consumption is more than two times the Total Climate Energy Consumption. While both graphs in Figure 4 shows an increasing trend during the summer of 2012, the graph of the Total Climate Energy Consumption shows a much more reasonable increase than its counterpart, which shows a two-fold increase in August (2012) alone.

The discrepancy between the energy consumption data for the cooling and ventilation systems and that for the entire building leads to the suspicion of how data is recorded by the Workplace Footprint Tracker. The data shown in Figure 2 certainly does not reflect the total electricity consumption in the University Library. This is confirmed after checking the Estate
Management’s Database (SystemsLink). According to the database, the Invoice Electricity Consumption$^{22}$ throughout the past four years has stayed consistently within the range 250,000-350,000 kWh. The close to 550,000 kWh energy consumption recorded in August, 2012 in Figure 2 is certainly problematic. Hence, this report questions how the summary diagram on the Workplace Footprint Tracker is produced.

Without clearly explaining what the diagram of the University Library Energy Consumption refers to, it would be difficult to study and understand the anomaly point in August, 2012 and the discrepancy between Figure 2 and 3.

Similarly, the diagram of the Total Climate Energy Consumption (Fig.3) lacks clarity, especially because different buildings/rooms have different start date of metering. Key energy-consuming buildings/rooms such as the North West Corner and the 1972 West Bookstacks were metered since December, 2011 as opposed to October 2011, when metering began in most of other buildings/rooms. Therefore, any increasing trend shown after December 2011 can be due to the addition of the new data, rendering the use of the diagram minimal.

**Buildings with Reading Rooms takes up the Most Electricity**

According to the League Table in the Workplace Footprint Tracker (Appendix III), library buildings with offices and reading rooms account for the highest usage of electricity. These buildings include the North West Corner, the South West Corner, the Aoi Pavilion and the 1972 West Bookstacks. These buildings contain all the major reading rooms in the University Library (except the Main Reading Room). These reading rooms usually spans across two storeys, taking up a large amount of space for cooling and ventilation.

At the beginning of the project, it was suspected that the repositories take up the largest proportion of energy consumption and hence they were made the subject of study. However, after examining the library buildings and the Workplace Footprint Tracker, it is realized that space in the repositories (specifically those with cooling and ventilation systems) are more efficiently used than those in the reading rooms. While book stacks in the cooled and ventilated repositories are mobile, tightly packed and span from the floor to the ceiling, most space in the reading rooms is empty. Hence, extra electricity is used to cool and move the air in the empty space of the reading rooms every day, driving up the energy demand.

Reading rooms in the library buildings have been built with consideration not in energy economy but in daylight strategy and aesthetics. The tall windows built high on the walls of the reading rooms allow maximum entrance of daylight without creating discomfort for their readers (glare). Also, the large empty space arouses a sense of majesty and solemnity, adding to the historical/cultural values of the Library. Hence, how to utilize reading space in an optimal manner would require a detailed and holistic study which this project unfortunately cannot accomplish in a month’s time.

**On User-friendliness**

Even though the Workplace Footprint Tracker employs a user-friendly artistic design and provides “Hints&Tips” to encourage behavioral change in using energy, many functions on

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$^{22}$ This refers to the electricity cost shown on the electricity bill.
this program still requires clarification. A beginner’s instruction manual should be provided to help users to understand and encourage them to explore the various functions of the program. It should include instructions on how to read the diagrams and how to utilize the functions in the Tool bar to extract, download and create charts and tables.

The author of this report believes that the Workplace Footprint Tracker should not be a whimsical innovation for users to see the energy usage of their buildings or rooms under a transient interest. Instead, it should be a tool that empowers the users to study the energy data of their buildings, discover the causes of issues displayed and seek for solutions. To move from a monitoring device to an interactive tool that inspires users to take action, the designers/operators of the Workplace Footprint Tracker (WFT) should consider a systematic feedback collection process for the program. The subject of the process should include not only the energy champions/managers of the pilot buildings tracked under the WFT, but also concerned staffs and students who are the potential users to carry out energy saving measures. Through studying feedbacks from a broad range of users, the designers of the WFT may be able to make the program more user-friendly.

**Real-time Measurement**

**Methodology**

Two types of sensors are used: three pairs of Tinytag Talk 2 Data Loggers and four Tinytag Ultra 2 Data Loggers. Each pair of Tinytag Talk 2 Data Loggers consists of a temperature logger and a relative humidity (RH) logger. Each Tinytag Ultra 2 Data Logger can collect temperature and RH data concurrently. Therefore, there are essentially seven data loggers capable of recording both temperature and RH conditions.

![Figure 5: three pairs of Tinytag Talk 2 Data Loggers (Tinytag Basic) and four Tinytag Ultra 2 Data Loggers (Tinytag Ultra) were placed on the shelf for benchmarking.](image)
As the Tinytag Ultra 2 Data Loggers (Tinytag Ultra for short) are more advanced (new, more accurate and have higher capacity), they are used to measure the more recently built repository buildings which are likely subject to low-level environmental fluctuation, in turns demanding a higher accuracy in measurement. The three pairs of Tinytag Talk 2 Data loggers (Tinytag Basic for short) are used to conduct measurement in repositories and non-repositories that are subject to less or no environmental control, which implies a possibly higher level of fluctuation in temperature and humidity.

Each data logger is set at roughly the center of a designated room for 24 hours, taking one reading every 50 seconds before being transferred to another venue. Tinytag Ultra has a higher capacity and is able to run for 9 days non-stop. Therefore, the four Tinytag Ultra data loggers can be directly transferred from one room to another once it completes its 24 hour data recording. On the other hand, the three pairs of Tinytag Basic can only run for a day, given that it takes reading every 50 seconds. Hence, each Tinytag Basic has its data collected daily and is reset for the next venue. Also, all the Tinytag sensors are allowed around half an hour buffer period to reach equilibrium with its surrounding atmosphere. This helps to minimize any residual impact the previous room’s environment has on the sensors.

All the Tinytags are placed on a fixed case in every designated room for measurement. This is to minimize disturbance caused by the movement of mobile cases. With the exception of the case studies, all the Tinytags are placed near the center of the room (both horizontally and vertically) to avoid thermal and hydroscopic influences from weak wall or floor insulations. Also, empty shelves are selected if available for placing the Tinytags. This is to avoid disturbance from human handling of documents on the shelves.

**Benchmarking**

As there are no available tools to recalibrate all the Tinytag loggers to ensure the accuracy of data collection, benchmarking is used. Benchmarking aims to adjust the data collected from each logger to be as close to the actual environmental conditions as possible.

All the Tinytag data loggers are benchmarked against one set of carefully chosen temperature and RH values. The three pairs of Tinytag Basic were placed at a selected location (near center) in West Bookstacks Ground Floor Room 3 (WB_G3 for short) on August 1. The four Tinytag Ultra were placed at the same location in the same room the next day. As WB_G3 situates in the Phase 6 building, one with the highest level of environmental control in the Library, the storage space is unlikely to be subject to external weather influence. Therefore, the effect of taking the data on adjacent days as opposed to the same day is minimal. (No change in the AHU, no influence from the external weather)

Below is a table of adjustment for each data logger after the benchmarking.

<table>
<thead>
<tr>
<th>Adjustment</th>
<th>Tinytag Basic</th>
<th>Tinytag Ultra</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td>T1 T2 T3 RH1 RH2 RH3 TRH1 TRH2 TRH3 TRH4</td>
<td></td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>0 +0.1 +0.3 0 -0.1 0 0</td>
<td></td>
</tr>
<tr>
<td>Relative Humidity (%)</td>
<td>-4 0 -6.7 -0.1 +0.1 +0.2 -0.2</td>
<td></td>
</tr>
</tbody>
</table>
Thus, all the data will be subject to the above adjustment prior to comparison. This will minimize the error in comparing the loggers’ data against each other or against a specific set of values (such as the Recommended Environmental Design Criteria in the guidelines).

Areas Covered

This real-time environmental monitoring lasted a total of nine days. Forty-four rooms in the Library buildings have been monitored, including repositories and non-repositories (such as reading rooms). They are:

- All repositories in Phase 5, 6 and 1972 West Bookstacks
- Most of the repositories in the North & South Pavilions
- Nine Major Reading Rooms
- Three Microfilm/Microform Storage Rooms
- Tower, North and South Courts (1934 Scott’s Building)
- Aoi Basement

A detailed list of areas covered is available in Appendix IV. All repositories, which are defined earlier as closed access rooms storing the four types of materials, have been covered. All the reading rooms (with the exception of the Digital Resources Area) have also had their environmental conditions measured.

Results and Analysis

In Appendix V, the real-time environmental data of each of the forty-four rooms measured is compared against the recommended environmental design criteria in the British Standard 5454 (2000) and the Published Document 5454 (2012). The result of the comparison is mapped onto the floor plans of the library buildings. Different signs are used to denote the level of compliance with the BS5454 and the PD5454 respectively.

Before proceeding to analyze the result, it is important to recognize that each room is monitored for only one day. Any conclusions drawn from the data cannot be generalized to represent the situation of the rooms as the monitored result can differ greatly in different seasons. Thus, instead of analyzing the data on a time scale (24 hours), this report analyzes the data of a room by comparing it with the storage guidelines and correlating it with the existing infrastructure of the room (environmental control systems).

Also, it is important to note that the criteria listed under the BS5454 and that under the PD5454 are different. According to Table 1 in “The Guideline” section, the BS5454 requires a 15-20°C for frequently handled materials, 12-17°C for infrequently handled materials and 30-65% RH for all materials. On the other hand, the PD5454 requires 13-20°C and 30-60% RH for mixed archive storage, 5-25°C and 25-60% RH for paper storage and 5-18°C and 30-50% RH for visual and audio media storage. Because of such difference in criteria, many rooms satisfy only one of the two guidelines.

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23 North Pavilion – Map Department; South Pavilion – Music Department
24 These rooms are: NWC Second Floor Bookstore 1 (Microforms), SWC Second Floor Microfilm Storage Room and SWC Fourth Floor Microfilm Storage Room. There are also First Floor Microfilm Room and Third Floor Microfilm Room labelled as “Microfilm” on the Cambridge Library Floor Plans. But as they are used for microfilm reading, they are not considered as microfilm/microform stores.
The maximum relative humidity allowed in a repository according to the BS5454 is 65%RH, whereas that according to the PD5454 is 60%RH (for mixed and paper storage). Hence, it is easier for a repository to satisfy the relative humidity criteria of the BS5454 as it sets a 5% higher upper limit than that of the PD5454. Upon comparing the data with the PD5454 criteria and creating the maps in Appendix V, the author of this report has taken into account that “brief periods (e.g. less than one day) between 60%RH and 64%RH represent only a slightly increased risk” in a mixed archive. Rooms with relative humidity above 60%RH for more than a few hours are considered to be failing the relative humidity criteria in the PD5454. This is a conservative approach to judge the environmental compliance of the rooms as it includes the possibility that the room conditions exceeds the environmental criteria for more than one day in other time of the year and hence creates non-negligible risk for the storage materials.

As it takes unrealistic amount of effort to distinguish the repositories based on the frequency of handling of their materials, this report use the 15-20°C as the BS5454 temperature criteria for all repositories. Only when the temperature ranges of the monitored rooms are lowered than 15-20°C are they being compared to the 12-17°C criteria for infrequently handled materials (labelled as BS* in Appendix V).

The maximum temperature allowed in a repository according to the BS5454 is 20°C (for frequently handled materials), whereas that according to the PD5454 is 25°C (for paper storage). Thus, eight out of the thirty-five monitored repositories are able to pass the PD5454 criteria for paper storage but fail the BS5454. These eight rooms are mainly repositories in the Tower, the Music Department and the Map Department. As these areas are all situated in the 1934 Scott’s Building and there is no environmental control system available, it is expected that they fail the British Standard. They are able to satisfy the PD5454 criteria for paper storage likely because the thermal mass of the external walls is high enough to reduce heat and humidity transfer between the repositories and the external environment. Based on visual inspection, documents stored in these repositories are generally intact. Even though these repositories are mixed archives storing not only paper but also parchments, leather and other types of more sensitive materials, they are considered under the laxer paper storage criteria of the PD5454 as paper takes up the majority of the storage materials. On one hand, it is important to recognize that many sensitive materials in the Tower and the Map and Music Departments are not preserved under a mechanically controlled environment. On the other hand, since the materials in these repositories are intact, it shows that a laxer standard can be applied to these repositories. As long as the sensitive materials are constantly inspected and maintained in good conditions, these repositories, though lacking environmental controls, can still be considered as passing the PD5454 criteria for paper storage.

Out of the forty-four rooms monitored, thirty-five of them are repositories and the other nine of them are the reading rooms. Out of the thirty-five repositories, only fifteen of them satisfy the environmental criteria listed under both the British Standard and the Published Document. Most of these qualified repositories are located in the Phase 5 and Phase 6 Buildings of the West Bookstacks, two buildings which are designed to “call for full compliance with BS5454

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25 Ibid. (2)
26 A room’s environment is mechanically controlled when it has heating, cooling and ventilation systems installed.
27 For a detailed list of sensitive materials and their associated environmental criteria for storage, please refer to Annex D of the PAS198:2012 - Ibid. (20)
and therefore [have] the most onerous environmental control requirement.”

As the ranges of temperature and humidity criteria listed under the PD5454 are similar to that under the BS5454 (refer to Table 1), the Phase 5 and Phase 6 buildings are thus also compliant with the Published Document.

Also, surprisingly, the North and South Courts on the ground floor of the 1934 Scott’s Building satisfy both the guidelines. Even though the original library building is not built to comply with any environmental standards for archival storage, air-conditioning systems have been installed into the North and South Courts for archival storage. This helps to maintain the environmental conditions of the rooms within the criteria of the guidelines. However, there are seven Perimeter Rooms surrounding the two Courts and they are not monitored. It is possible that these rooms act as a buffer zone between the Courts and the external environment (as the Central Corridor is exposed to external air through the Main Entrance). The buffering effect allows slower effect of loss and gain of heat and humidity therefore keeping the conditions of the two Courts satisfactory against the guidelines.

It is worth noticing that all five rooms of the West Bookstacks Basement, though recently built and environmentally controlled, fail to satisfy the environmental criteria in both the BS5454 and the PD5454. The West Bookstacks Basement stores many sensitive and valuable materials including the Royal Common Wealth Society Collection; failing to comply with the BS5454 or the PD5454 may be risky to the storage materials. Even though the data does not cover a sufficiently long period of time to show that the environmental control in those rooms is not compliant to the criteria, the unanimously high humidity across the Basement does reveal a possible problem in its air-handling unit that requires further investigation.

Amongst the thirty-five repositories monitored, three of them are microfilm/microform stores. The monitored conditions of these stores are compared against the regular BS5454 criteria and the PD5454 criteria for visual and audio media storage (cool storage). As the criteria for cool storage under the PD5454 is stricter, all three store rooms fail to pass the PD5454 standards. Also, two of the stores fail to pass the relatively laxer BS5454, signifying that the video and audio media in the University Library lack sufficient environmental control. Microfilms and microforms are concentrated in these three stores. Even though there are similar materials stored elsewhere, these three stores present a typical case of the lack of environmental control for visual and audio materials, which are more sensitive than regular storage materials such as paper and parchment.

Out of the nine major reading rooms, seven of them are compliant with the criteria for **Reading Room Environment** listed under the PD5454. The BS5454 criteria are not applied to the reading rooms as the British Standard lacks a distinct set of environmental criteria for the reading room. It is surprising to see that the environmentally controlled Rare Books and Manuscript Reading Rooms fail to comply with the PD5454 during the monitored period while rooms such as the Main Reading Room and Map Reading Room which lack any

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29 According to section 4.10.2 of the PD5454, the temperature range is 13-25°C and the relative humidity range is 40-65%RH. *Ibid.* (2)

30 According to 7.3.1 of the BS5454: “in order to avoid the need for acclimatization…when documents move from storage to reading room and back, the temperature should be at a fixed point between 16°C and 19°C with a tolerance of 1°C on either side…” In this statement, “the temperature” refers to the storage temperature as indicated by the title of the section. Upon perusing the document, there is no distinct criteria for reading room environment listed in the BS5454.
environmental control\textsuperscript{31} comply with the guideline. On one hand, failure of compliance for the Rare Books and Manuscript Rooms shows a possible optimization problem with the BMS-controlled air handling units in the North West Corner. On the other hand, reading rooms that are not environmentally controlled can reach the criteria likely because the external weather is milder in the summer (when the monitoring occurs) hence less impactful on the room conditions, but whether these reading rooms are still able to comply with the guideline in other seasons is unclear.

The data obtained from the real-time monitoring is further compared with the BMS data. This is done by visual comparison of the graphs of the BMS data and the monitored data. As currently data cannot be extracted from the BMS, it is not feasible to conduct a quantitative analysis between the two sets of data. Based on the visual comparison, the real-time monitored data roughly agrees with the BMS data though there are some minor differences in the values. A systematic comparison between the two sets of data requires the BMS to be data-extractable and downloadable and a tremendous amount of time and effort which is not realizable in this project.

Last, graphs of the temperature and humidity conditions of each room monitored are presented in Appendix VI for reference.

**Case Studies**

As only one set of environmental data is collected for each of the rooms monitored and most of the data are taken on different days, conclusions cannot be directly drawn upon the comparison of collected data across rooms across the Library. Instead, three case studies are proposed and investigated.

1. **Does secondary glazing really help?**

In certain parts of the Library, such as the Map Room B and North Pavilion, secondary glazing is installed for heat insulation. Research conducted by the Technical Conservation Group of Historic Scotland shows that secondary glazing can reduce heat loss from window by 63\textsuperscript{\%}.\textsuperscript{32} However, heat loss of a room is often complicated by other factors. To examine the effectiveness of secondary glazing, a one-day controlled experiment is conducted at two adjacent repositories in the North Front, Ground Floor of the 1934 Scott’s Building.

Room 1 has been installed with secondary glazing while Room 2 has only single glazing windows. Room 2 was originally opened to readers but was closed for storage purpose; thus it did not receive a secondary glazing installation. These adjacent rooms are chosen to minimize the influence of other external factors such as room orientation and altitude, which can bring about differences in environmental conditions. Also, both rooms do not receive any form of ventilation (mechanical or natural). This eliminates the confounding impact of mechanical ventilation on the comparison of the two room environments.

\textsuperscript{31} Besides radiators, these rooms cannot be cooled, heated, ventilated under a controlled manner.

One pair of Tinytag Basic is placed in each of the two rooms for 24 hours. These two pairs of sensors are located as far away from the wall that separates Room 1 and 2. As the temperature and humidity near the two sides of the wall can be similar, placing the two pairs of Tinytag Basic further away from each other will minimize any influence of poor wall insulation. The temperature and humidity data plotted against the time of monitoring is shown in the diagrams below. Also, the Cambridge weather data during the period of experiment is also extracted and plotted into the same diagrams for comparison.

As shown by the above diagrams, Room 1, which carries secondary glazing, enjoys a two degree lower temperature ($T$) than Room 2 throughout the 24 hours of monitoring. Even though the relative humidity (RH) is slightly higher in Room 1 (as expected, due to the inverse relationship between $T$ and RH), its RH is still well below the upper limit of 60% RH proposed in PD5454. Hence, it can be tentatively concluded that secondary glazing has a noticeable impact on the temperature of a non-ventilated repository.

Meanwhile, as shown by the difference between the green lines and the others, the dramatic changes in external temperature and relative humidity conditions in Cambridge has no discernible impact on the environment of the two monitored rooms. Room 1 and 2 are located in the 1934 Scott’s building, the building of the lowest environmental design criteria amongst all the University Library buildings. Thus, it is safe to assume that all other repositories and reading rooms, as long as they are not naturally ventilated (either mechanically ventilated or receives no ventilation), are not subject to the influence of the external weather.

Currently, non-ventilated repositories similar to Room 1 and 2 include the repositories in the Northeast and Southeast Corners of the 1934 Scott’s Building (where Maps and Music...
departments locate respectively) and those in the Tower (from 7th to 17th floor). Besides three rooms in the Northeast Corner 33, all the non-ventilated repositories have single-glazing windows. Even though it is beyond the scope of this project to quantify the potential energy savings brought about by the secondary glazing on these non-ventilated repositories, this case study demonstrates that the impact of secondary glazing is positive and discernible. Besides the repositories in the Tower, all other non-ventilated repositories have installed hot-water radiators. Installing secondary-glazing on these repositories can potentially reduce heat loss and cut energy output from the Central Gas Boiler, which sends hot water to radiators in almost all of the Library buildings (besides the Rotherham Building).

2. Does natural ventilation really affect the temperature and humidity conditions?

A number of rooms in the Library, repositories or not, lack mechanical ventilation. Natural ventilation is used as the alternative to provide air circulation and fresh air inflow in order to reduce accumulation of moisture in certain parts of a room and thus the possibility of mould germination. However, natural ventilation also carries the risk of introducing external heat, moisture, spores or polluted air (with chemical molecules such as sulphur dioxide) to the rooms. Due to the limitation of the testing equipments, this case study focuses only on the impact of natural ventilation on the temperature and humidity conditions of a room.

Another key reason for the case study is that most of the 1934 Scott’s Building uses natural ventilation. Even though many of those areas are not closed-access rooms for document storage (hence are not repositories, as defined earlier in the report), areas such as the Map Reading Room, North and South Wings, North and South Fronts and a number of librarians’ offices 34 store important archival materials such as pre-1989 books, maps and music scores which are both rare and valuable. These rooms, defined as the open-access storage areas in this report, are naturally ventilated, where windows are opened for cooling, human comfort and air circulation. Hence, it becomes imperative to understand the impact of natural ventilation on these storage areas.

A one-day control experiment, similar to that in the first case study is conducted in the two adjacent map rooms in the Northeast Corner of the 1934 Scott’s Building. The Map Reading Room (Room A) is naturally ventilated while the main Map Storage Room (Room B) does not have any ventilation system installed. Room B thus serves as a negative control for Room A. Adjacent rooms are chosen, similar to the first case study, to reduce external confounding factors such as room orientations. Even though Room A is a reading room, most of its space is utilized for the storage of valuable maps. With its windows being opened every day at 9am and closed at 5pm 35, Room A faces any risk brought about by the external air. Thus, Room A offers a representative case for the study of impact by natural ventilation on all other open-access storage areas in the University Library.

One pair of Tinytag Basic is placed in each of the two rooms for 24 hours. The temperature and humidity data plotted against the time of monitoring is shown in the diagrams below. Also, the Cambridge weather data during the period of experiment is extracted and plotted into the same diagrams as a reference.

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33 These three rooms are: the Map Room B (Ground Floor) and the North Pavilion Basement Rooms (two connected rooms).
34 Geoffrey Keynes, Stefan Heym, Bradshaw
35 The report lacks the information on how natural ventilation is utilized in winters.
As shown by the above diagrams, the naturally ventilated Room A shows little difference in temperature and relative humidity from that of the non-ventilated Room B during the 24 hours of monitoring. Room A has a slightly higher temperature, most likely due to its adjacency to the Dining Room in the Rotherham Building. However, considering that the windows were opened for 8 hours and Room A’s environment is almost as stable as its negative control, the impact of natural ventilation on temperature and relative humidity is not significant during the monitoring period.

Upon careful comparison among the three lines in each diagram, it can be observed that the yellow line in each diagram slightly follows the trend of the green line. This means that the temperature and humidity variation in Room A is slightly related to the external weather variation. However, given the large difference in magnitudes between the two lines, it can be safely concluded that external weather has little influence on the naturally ventilated Room A during the period of experiment. This is a reasonable conclusion because the size of the windows is small compared to the Map Reading Room; the air exchange through the window is thus limited.

As mentioned at the beginning of this case study, the open-access storage areas in the 1934 Scott’s Building uses natural ventilation, stores documents and provides reading space. In summer, natural ventilation helps to cool the storage areas, increase air circulation and provides human comfort. Yet, the cooling, air-circulating and human-comforting functions of natural ventilation are prone to conflicts upon different weather conditions. In winter, if human comfort takes priority over air-circulation and windows are closed, the storage
material may face the risk of mould germination (especially if internal heating is insufficient to provide a dry condition). Yet, favouring air-circulation can lead to readers’ discomfort. Such conflict of priorities can intensify in spring and autumn due to the more unstable weather conditions. For instance, on a warm day in spring, if windows are closed to avoid the influx of mould spores while the radiators are on, the room will face the risk of overheating and the readers will experience discomfort. Thus, this report recognizes the need to optimize the benefits of natural ventilation in the open-access storage areas throughout the course of a year, as it directly concerns the preservation of archival materials and the comfort of library readers.

From an energy perspective, natural ventilation can lead to both electricity and gas savings for the Library. Currently, library buildings that hold mostly non-repositories are mechanically ventilated 24 hours a day, bringing about unnecessary energy consumption during the off hours. Such energy wastage can be reduced under a discreet plan concerning the alternating usage of natural and mechanical ventilation. Automatic/manual duct shutters can be installed at desired locations such that air will only be directed to specific rooms during the off hours. Temperature and humidity sensors can be installed in the non-repositories for environmental monitoring. Staffs working in those non-repositories will receive workshops on switching between natural and mechanical ventilation by opening/closing the windows based on the readings of the sensors. Accessing the costs and benefits of this plan will require a professional analysis which is beyond the scope of this project.

3. Do adjacent rooms affect each other?

Upon the examination of data from the Building Management System (BMS) in all the rooms of the Phase 5 and Phase 6 Buildings, it is found that temperature and relative humidity readings collected from sensors in the east-end are higher than those collected from sensors in the west-end. Therefore, it is suspected that because the west walls and east walls of the Phase 5 and 6 Buildings are exposed to the cooler external environment and the warmer 1972 West Bookstacks respectively, a temperature gradient is created. Also, Phase 5, Phase 6 and the 1972 West Bookstacks are built under a decreasing order of environmental design stringency and are adjacent to one another. Thus, each building is probably subject to influence from the external weather and the heat transfer with its two adjacent buildings. To verify such mutual influence between buildings, a one-day controlled experiment is conducted at Room 2, on the third floor of the Phase 5 Building.

Room 2 is a typical representation of a repository. It is closed-access, has a temperature set point of 15°C and stores manuscript archives. As it is located in the Phase 5 building, it enjoys the second highest environmental design criteria amongst that of all library buildings. However, the Stage D Report of the Phase 6 Building reveals that the Phase 5 Building has poorly insulated floors such that “the heat transfer between floors was found to be far greater than through the external fabric even with the relatively small temperature differences being considered.” Also, quality of wall insulation in the Phase 5 Building is not mentioned, it is

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36 Especially the non-reading rooms in the North West and South West Corners and the Aoi Pavilion
37 In this case, the reading rooms in NWC, SWC and Aoi should be mechanically ventilated, as they store a considerable amount of rare books, official publication and manuscripts.
38 Refer to the Stage D Reports of the Phase 5, Phase 6 and 1972 West Bookstacks
39 Ibid. (28)
thus suspected that walls that adjoins the Phase 5, the Phase 6 and the 1972 Building are prone to heat transfer.

In this case study, Room 2 is the designated room for environmental monitoring and it considers the influence from its neighbours: Room 1 from the 1972 West Bookstacks, Room 3 from the Phase 6 Building and the external environment. To assess such influence as closely as possible, three pairs of Tinytag Basic are placed in proximity to the walls that are adjacent to Room 1, Room 3 and the external environment respectively. That means each pair of Tinytag Basic measures the temperature and relative humidity conditions near a wall that is bordering Room 2 and its neighbour. Thus, if the local temperature near the wall rises or drops slightly due to the heat transfer from the neighbour environment, the minute change can be captured by the sensors due to its proximity to the wall.

Even though it is found that repositories in Phase 5 have poor floor insulation, this experiment sets out to measure mainly wall insulation. This is because: first, all repositories in Phase 5 share the same temperature (T) and relative humidity (RH) set point, hence the T/RH difference is likely to be minimal; second, setting up the sensors will be difficult, as one pair of sensors has to be fixed to the ceiling; third, all three pairs of sensors are placed near the centre point between the floor and the ceiling so as to reduce any influence from rooms above and below.

The temperature and humidity data plotted against the time of monitoring is shown in the diagrams below.
The Cambridge weather data is not included in the graphs mainly because the Phase 5 Building is built to fully comply with BS5454, thus possessing a high level of air tightness unlikely influenced by the external weather. This can also be shown by the flat and smooth lines in the temperature diagram, which indicates that external temperature fluctuation has minimal impact on Room 2’s temperature as a whole.

Still, as the average external temperature is around 17.1°C during the period of monitoring, more than two degree Celsius higher than the temperature set point of Room 2, the wall would be slightly warmer than the average room temperature. This is evident in the temperature diagram. The red line is 0.4°C above the orange line and 0.9°C above the yellow line. This means that the external wall in Room 2 has a higher temperature than the wall that adjoins Room 2 and 1, which is warmer than that adjoins Room 2 and 3. Hence, the external wall has possibly filtered away the external temperature fluctuation but absorbs heat during that process, thereby slightly heating up the air around it.

Even though Room 1 has a temperature set point of 17.5°C and the ambient temperature is 17.1°C, the temperature diagram shows that the wall that adjoins Room 1 and 2 is 0.4°C lower than the external wall. This is possibly because of the ductworks embedded in the wall between the Phase 5 and 1972 Buildings. The ductworks transport cool exhaust air from the basement to the roof, thereby also cooling the wall surrounding them.

The wall adjacent to the Phase 6 Building registers the lowest temperature readings. This is because the temperature set point of Room 3 in Phase 6 is 15°C while it enjoys a better thermal insulation than Room 2 in Phase 5. Thus, even though these two rooms share the same temperature set point, Room 3 is less prone to heat gain, thus having a lower temperature than that of Room 2.

On the other hand, the relative humidity readings at the three walls in Room 2 follow a reverse order in magnitude. The wall that adjoins Room 2 and 3 is more humid than that adjoins Room 1 and 2, which in turns is damper than the external wall. This result is expected, as relative humidity in a repository generally forms a reverse relationship with the local temperature. Hence, a lower local temperature corresponds to a higher relative humidity.

Even though the difference in environmental conditions at different parts of Room 2 is subtle, it demonstrates that a local hot (and dry) spot or cold (and damp) spot can be formed in a room because of the influence from its adjacent room. This is evident from the stable temperature and humidity readings in the previous diagrams. The temperature and humidity conditions near each wall in Room 2 remain the same throughout the period of monitoring, meaning that the air near each wall remains warmer/cooler than the other parts of the room, hence forming a hot/cold spot. This on one hand shows that the air distribution system is not powerful enough to remove the local hot spot and cold spot. On the other hand, it shows that the heat transfers between Room 2 and its adjacent rooms (including the external wall) are constant and persistent.

Room 2 situates in one of the most thermally insulated buildings. Yet, it carries subtle local hot spots and cold spots due to influence from adjacent rooms. Therefore, in most other

repositories, reading rooms and open-access storage areas in the Library, where there is less thermal insulation and weaker ventilation system, local hot/cold spots are expected to be much more prevalent and more severe. This can mean local accumulation or deficiency of moisture which can lead to mould germination or physical damages to the organic materials.\textsuperscript{41}

Therefore, adjacent rooms can affect each other’s environment through heat transfer. The impact of such influence will intensify in rooms that are not built with strong thermal insulation and air distribution system. Local hot or cold spots can form in regions of a room due to the heat transferred from and to its adjacent rooms, increasing the risk of mould germination and other damages to the storage materials. One realistic example of such situation is in the 1934 Scott’s Building.\textsuperscript{42} Heating pipe works in this building have not been maintained for decades. Many of them are blocked by sludge but some are still working. These pipes are embedded in walls that enclose the open-access storage areas in the Scott’s Building. It has been recorded that some parts of the walls in the building are significantly warmer than others. This can easily create local hot and cold spots which rapidly increases the risk of mould germination and desiccation of materials. As the building has no mechanical ventilation in this building (except the North and South Courts), tens of thousands of stored materials are facing the risk of damage every day. In a long run, this will create a possibly large and unnecessary amount of effort in the restoration of damage materials.

\section*{Conclusion}

The University Library is chosen as one of the five Pilot Buildings for energy improvement under the Energy and Carbon Reduction Project. To carry out the ECRP successfully in the University Library, one has to find the balance between energy reduction and archival conservation. This report has explored the environmental conditions and energy usage in most parts of the Library through the BMS, the Energy Dashboard and a period of Real-time Measurements. It also studies and compares the BS5454 (2000) with the PD5454 (2012) in the context of the Library.

The author of this report reckons that the balance between energy reduction and archival conservation in the ECRP-Library project is essentially a choice between optimizing and stabilizing the environmental conditions. The current approach in the University Library is to prioritize the conservation of archival materials hence making minimal changes in the environmental settings of the heating, cooling and ventilation systems. However, given that acclimatization is not available in the Library, the frequent transfer of library materials across significantly different environments renders the stabilizing approach unsound.

Upon defining the repositories with Dr. Jill Whitelock, the Head of Special Collections, the author of this report is able to distinguish repositories from reading rooms and areas later defined as the open-access storage areas. As the environmental data on the BMS is not downloadable, the author of this project collects real-time data of forty-four repositories, reading rooms and open-access storage areas during a short period of environmental monitoring. The data may be rudimentary as a one-day monitoring in each room is not sufficient to represent the room environment throughout a year. However, the monitoring is

\textsuperscript{41} Ibid. (20)
\textsuperscript{42} Information obtained from the Building Manager of the University Library – Richard Hardy
Shi, Yi 26
carefully planned to minimize the disturbance to achieve a certain level of confidence and accuracy.

The result and analysis reveal that most of the repositories and reading rooms with environmental controls satisfy both the BS5454 and the PD5454 criteria during the period of monitoring. On the other hand, many other repositories in the Library, such as the Tower, the Music and the Map Departments in the 1934 Scott’s Building, lack environmental controls and hence not satisfy either one of the two guidelines. Yet, upon visual inspection and consultation with the staffs of the Special Collection, most of these library materials remain intact. This does not at all mean that environmental control is unnecessary, but demonstrates that many library materials carry a reasonable level of tolerance against in-door environmental fluctuations. This thus gives the author of this report the confidence to propose the flexible set point mechanism, which seasonally and gradually adjusts the environmental control settings in the repositories for energy economy.

The flexible set point mechanism gradually increases/decreases the temperature setting of an air-handling unit by only 2°C across a 10-12 week period. A simple model demonstrates that such mechanism, which can be changed on a master control of the BMS, can result in a 7.1 percent reduction in the total cost of electricity in 2011. Even though the model is rudimentary and does not take the full range of factors into consideration, it demonstrates the possible energy impact that a simple change in temperature setting can provide. This report further consolidates its proposed mechanism through another simple model by demonstrating that the 2°C change across a 10-12 week period will not damage paper or leather documents. The discussion of the flexible set point mechanism is placed in the earlier section of the report to highlight the importance and feasibility of optimizing, as opposed to stabilizing, the environmental conditions in the Library. Hence, the author of this report urges for a detailed investigation of the impact of the flexible set point mechanism in the future, as it matches the fundamental idea behind the collaboration between the Estate Management and the Library – to improve the energy economy of the Library without compromising the integrity of its archival materials.

A brief analysis of the data from the Energy Dash Board reveals not only the issues with the Work Place Footprint Tracker but also the energy usage of the reading rooms. The Northwest Corner, the Southwest Corner, the Aoi Building and the 1972 West Bookstacks all contain large reading rooms with low space efficiencies which lead to an electricity consumption even higher than that of the cooler repository buildings (Phase 5 and 6). Hence, reading rooms may also adopt a flexible set point mechanism to help reduce their energy usage. Yet, the environmental conditions of reading rooms are further complicated by the factor of human comfort, which requires a different study beyond the scope of this project.

This report also presents the Published Document 5454 (2012) as a more suitable alternative for the University Library than its earlier counterpart (BS5454). This is not only because the PD5454 defines environmental criteria realistic and applicable for environmental assessment in the Library, but also because it approaches archival storage with an emphasis on energy economy, which is directly related to the purpose of the ECRP at the Library. The PD5454 is based on more than a decade long research on archival conservation since the release of the BS5454 in 2000. Since March 2012, the BS5454 has officially been replaced by the PD5454. Because of the traditional stability approach, library archives around the United Kingdom have yet to adopt the new guideline. The author of this report recognizes the leadership of the University of Cambridge in the nation and is confident that the Cambridge University Library
Shi, Yi 27

will lead the other UK library archives by first adopting the PD5454 as the guideline for its energy reduction endeavours.

**Recommendations**

Many recommendations have been made throughout this report and the three most important ones have been highlighted in the conclusion of the report: adopting an optimizing approach, further considering the *flexible set point mechanism* and replacing the BS5454 with the PD5454. This section focuses specifically on the recommendations for the sustainable design and effective storage in the University Library.

**Sustainable Design**

**Secondary Glazing**

Based on the first case study in this report, secondary glazing may potentially reduce gas consumption on the hundreds of radiators around the Library in the winter by hindering heat loss through the windows. A detailed cost-benefit analysis is needed to compare the cost of secondary glazing installation with the gas spending.

**Natural Ventilation**

Based on the second case study in this report, natural ventilation can bring about energy savings upon careful planning. One discreet plan proposed in the report concerns the alternating usage of natural and mechanical ventilation. Automatic/manual duct shutters can be installed at desired locations such that air will only be directed to specific rooms during the off hours. Temperature and humidity sensors can be installed in the non-repositories for environmental monitoring. Staffs working in those non-repositories, especially the reading rooms, will receive workshops on switching between natural and mechanical ventilation by opening/closing the windows based on the readings of the sensors. Accessing the costs and benefits of this plan will require a professional analysis which is beyond the scope of this project.

**Wall Insulation**

Based on the third case study in this report, adjacent rooms affect each other through transferring heat/humidity through the walls, creating hot/cold spots. These spots can result in mould germination or desiccation of the document in a long run. The full impact of the hot/cold spots cannot be assessed in this project given the short time period and the lack of advanced knowledge and technologies.

**AHU Design**

This is not being brought up in previous sections of the report. Based on the Stage D report of the Phase 6 West Bookstacks Building, the second and third floors of the building are designed to be 3°C lower the other floors for the storage of manuscripts and rare books. However, because there is only one air-handling unit for the entire building, exhaust air from

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43 In this case, the reading rooms in NWC, SWC and Aoi should be mechanically ventilated, as they store a considerable amount of rare books, official publication and manuscripts.
all floors is mixed and cooled down to the lower temperature that fulfils the requirement of the second and third floors. While some of the cool air is bumped to the second and third floors, more of it is reheated up to be bumped to the ground, first and fourth floors. This process is rather inefficient as a large amount of energy is consumed in cooling down all the exhaust air and reheating more than half it back up. Similarly, in the 1972 West Bookstacks where the fourth floor is kept at 20°C for readers’ comfort, similar energy wastage occurs. Even though it is opened as a reading space, the occupancy rate is low, leading to a low space efficiency and unnecessarily high energy consumption.

Currently, in the Phase 6 Building, as the other floors have a temperature criteria of 17°C ± 1°C where the second and third floors has a temperature criteria of 14°C ± 1°C,\(^4^4\) the Building Manager of the Library has adjusted the temperature setting of the second and third floors to be 15°C and that of the other floors to be 16°C. This way reduces the temperature difference between the exhaust air from the second and third floors and the rest, hence cutting the energy spending in cooling and reheating air. Yet, based on the PD5454, materials can be kept in the range of 13-20°C in a mixed archive. Thus, it is doubtful if such temperature difference needs to be maintained at all. The temperature criteria of the second and third floors are set by the Library based on the BS5454:2000. Since the BS5454 has been replaced by the PD5454, the temperatures of all floors in the Phase 6 Building can essentially be the same. Therefore, erasing the temperature difference between the floors in the Phase 6 can be a first step the Library take in adopting the PD5454 as a guideline for archival storage.

The fourth floor of West Bookstacks should be reconsidered for transforming back to a repository. Such renovation requires a cost-benefit analysis that favours the repository over the reading room option which is beyond the scope of this project.

**Effective Storage**

**Categorizing and Separate Management**

Even though the PD5454 has listed out three broad categories that almost all the Library materials fit in (Mixed, Paper, Visual&Audio), many repositories in the University Library still store a mixture of these three categories of materials. Hence, one suggestion is to group the same type of materials in the same repository to facilitate more effective environmental settings. As the three categories of storage materials have different temperature criteria, the best energy economy can be achieved when the three kinds of materials are stored and managed separately.

For example, the microfilm cases, which are often found in the same repository as the book shelves can be stored in Phase 5 which has a temperature setting of 15°C; the valuable manuscripts can be mixed with other rare books and placed in 1972 West Bookstacks’ repositories which has a temperature setting of 17.5°C; the paper documents can be boxed and placed in one of the Tower of the 1934 Scott’s Building which doesn’t have any environmental control but the buffer of the walls. Subsequently, the flexible set point mechanism can be employed to change the temperature settings of the repositories according to season without exceeding the criteria.

\(^4^4\) *Ibid.* (28)
Suppose it is in the summer, then the temperature setting of the microfilm cases’ repository can be raised to 18°C and 19.5°C for the valuable manuscripts. In this case the air-handling units avoid spending a significant amount of electricity in making the air 2°C cooler without violating the criteria given by the PD5454. Also, putting the less important paper documents into repositories that are not environmentally controlled can give space to more valuable manuscripts and rare books which many are still in the open-access storage areas or less controlled repositories.

However, if it represents an overwhelming labor cost to at least separate one category of material from another, then extra caution is needed in environmental monitoring. For example, a temperature reasonable for the paper documents (24°C) can be risky to the microfilms. Therefore either extra effort is spent in setting up a more complicated warning system on the BMS or it is needed by the person-in-charge in monitoring real-time.

Managing by Values

Another recommended way of effective storage is to store materials according to their values. Even though the Library does not record the values of all its storage materials, the most valuable manuscript archives and rare book collections are known. Yet, not all of the most valuable library materials are placed in the best environmentally conditioned rooms. For instance, the invaluable Charles Darwin’s manuscript archives are stored in Room 1, on the third floor of the 1972 West Bookstacks (WB3_1). It is known that the 1972 West Bookstacks has a poorer environmental design than Phase 5 and 6 and fails to provide WB3_1 the environmental conditions that satisfy either the BS5454 or the PD5454. Therefore, the Charles Darwin collection should be stored instead in either the Phase 5 or the Phase 6 buildings which are designed for full compliance to the BS5454. The most valuable collections should be stored in the most environmentally secured repositories as a practice of energy economy. Currently, it is unrealistic to equip all repositories around the Library with environmental control system to fully comply with the national storage guidelines. Therefore, an economical way of practicing both archival conservation and energy saving is to categorize the archival materials in terms of their values and match each category of materials with a repository building designed with a certain level of environmental control. A schematic diagram of all the Library buildings is presented below for future reference. The environmental design criteria of each University Library building (available from the Stage D Reports) is compared against the recommended environmental design criteria of the PD5454:2012 and rated according to a color scale.
As shown in the above diagram, Phase 6 is the building of the highest level of environmental design, followed by Phase 5, and then the Northwest and Southwest Corners and the Aoi Pavilion. As the Stage D Report of the 1972 West Bookstacks is not available, it is assumed that it is built under a lower environmental standard as compared to the more recent Aoi Pavilion etc. The 1934 Scott’s Building is not built under any available archival storage guideline hence carries the lowest level of environmental design. The above diagram has provided a rough overall picture of the environmental design of the Library buildings. Once the library materials are categorized (or some, as a first step) by their values, they can be transferred to different Library buildings for long-term storage. In this way, a specific range of values of archival collections is paired up with a building of a specific environmental design. The best repository can thus preserve the most valuable materials. Less valuable materials will be transferred to a less environmentally stringent repository to allow the more valuable materials to be preserved under a higher level of environmental control. Even though it is difficult to carry out such assortments and transfers in a large scale, small-scale attempts (intra-departmental or between repositories of the same floor) should be encouraged to build the momentum towards fully utilizing the benefits that the more advanced repositories can provide. Also, further work may be needed to specify the rating process of the environmental design criteria.

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**Bibliography:**

Appendix:

Appendix I: Model for the Calculation of Energy Savings via the Flexible Set Point Mechanism

Currently, the area of the repositories, reading rooms and the other open-access storage areas such as the North and South Wings in the 1934 Scott’s Building is 30301 m$^2$. The area of the offices is 2455 m$^2$. However, as the air-handling units in the library buildings do not cover some of the open-access storage areas (besides the reading rooms), the total area of consideration is approximated as:

Total Area Covered by air-handling units, $A = (30301 \text{ m}^2 + 2455 \text{ m}^2) \times 0.8 = 26,204.8 \text{ m}^2$

The height ($h$) between two Library floors is assumed to be 3 metres. The density of air ($\rho_{\text{air}}$) is taken to be 1.204 kg/m$^3$ at 20°C, 1 atm.\(^{45}\)

According to the available Stage D Reports of the Library extensions\(^{46}\), almost all of the air-handling units carry an air exchange rate of 4 air-changes per hour. Also, the percentage of fresh air intake varies from building to building (from 5% to at least 50%). Hence, the percentage of fresh air intake is assumed to be 50%.

Hence, the mass of fresh air being heated every hour is:\(^{47}\)

$$M_{\text{fresh air being heated every hour}} = A \times h \times \rho_{\text{air}} \times 4 \times 50\% = 189,303 \text{ kg}$$

If the temperature set point is adjusted to be 2°C higher or lower according to the flexible set point mechanism, then an amount of energy is saved from heating up or cooling down the mass of fresh air every hour.

The specific heat capacity of air ($c_{\text{air}}$) is assumed to be 1.005*10$^3$ J/kg·K, at 20°C, 1 atm.\(^{48}\)

The change in temperature ($\Delta T$) is 2°C according to the mechanism.

This amount of thermal energy being saved every one hour is:

$$Q_{\text{fresh air/hour}} = c_{\text{air}} \times M_{\text{fresh air/hour}} \times \Delta T = 105.694 \text{ kW·h}$$

The Coefficient of Performance of the air-handling unit is assumed to be 3.56 which is equivalent to an Energy Efficiency Ratio (EER) of 12.

\(^{45}\) The value is taken at 20°C as the average temperature in Library area of consideration is estimated to be around 20°C based on the real-time measurements.

\(^{46}\) Stage D Reports are available for Aoi Pavilion, North West Corner, South West Corner, West Bookstacks Basement Extension, Phase 5 and Phase 6. The air exchange rates in North and South Court of the 1934 Scott’s Building and those in the 1972 West Bookstacks are also assumed to be 4 air-changes per hour.

\(^{47}\) Here, it is assumed that the recirculated air does not drop in temperature which in reality it does. Heating up the cooled recirculated air also contributes to extra energy consumption. Meanwhile, many newer extensions have around 10% fresh air intakes. Hence, the 50% estimate for the percentage of fresh air intake sets out to compromise the extra energy consumption in the heating of recirculated air which is not considered in the model.

\(^{48}\) Ibid. (27)
Hence, the energy used by the air-handling units in the Library per year is:

\[ E_{\text{AHUs/year}} = \frac{Q_{\text{fresh air/hour}}}{\text{COP}} \times 24 \times 365 = 260,080 \text{ kW·h} \]

Assume the cost of electricity to be 9 pence per kilowatt hour, the energy saving from the flexible set point mechanism is:

\[ \text{£ energy savings/year} = 0.09 \times 260,080 \approx £23,407 \]

A Specific Example that Shows the Weakness of the Current Stability Approach in the University Library

As acclimatization is not available in the University Library, all the documents, including valuable rare books, official publications and manuscripts, are directly transferred between the repositories and the reading rooms.

Take the Manuscript Collection for example. Room 2 on the third floor of the Phase 5 Extension stores valuable manuscripts and archives. These documents are transferred to the Manuscript Reading Room in the North West Corner upon readers’ requests. According to the Building Management System, the temperature and humidity set points of Room 2 are 15°C and 50% RH and those of the Reading Room are 21°C and 50% RH. Hence, any documents that are moved across those two rooms will at least experience a 6°C sharp temperature change.

Also, it is known that there is no cooling and humidity control in the lobby that connects Room 2 and the Reading Room. Hence, the lobby’s temperature and humidity will fluctuate significantly in different seasons and at different time of a day. In summer, the temperature in the lobby is expected to be higher than both Room 2 and the Reading Room during the working hours. Hence, any document moved from Room 2 will first experience a sharp and larger than 6°C temperature rise before experience a drop in temperature upon entering the Reading Room. Upon moving back from the Reading Room, the document will first experience a (small or large) rise in temperature before encountering a larger than 6°C temperature drop. Similarly, documents will experience significant rise and drop in temperature in winter. Therefore, a document has to experience 4 environmental changes every time it is borrowed for reading.

Similar issues are experienced by documents in all other cooled repositories when they are transferred upon readers’ requests. Hence, most of the documents, as long as they are borrowed and transferred, are not kept in a stabilized condition. As the frequency of handling increases, the documents are inevitably exposed to a higher risk of physical damage due to the significant environmental changes they experience upon each handling.

Appendix II: Model to Calculate the Thermal Response Time

In this model, leather-covered books are considered, as they take up a significantly large proportion of valuable rare books and manuscript archives in the University Library. Every leather-covered book has six faces; only three are covered by leather. Hence, the exposed

49 The Manuscripts Reading Room has a temperature deadband of 1°C and a humidity deadband of 2%RH.
paper surface also provides grounds for investigating the thermal response time of a paperback. Thus, essentially this model considers both leather-covered and paper-back books, covering the majority of collection materials in the Library.

Four scenarios are investigated in this model:

Scenario 1: The leather side (Side A) of a shelf of common A4 size, leather-covered books
Scenario 2: The paper side (Side B) of a shelf of common A4 size, leather-covered books
Scenario 3: The leather side (Side C) of a shelf of A1 size, leather-covered large format storage materials
Scenario 4: The paper side (Side D) of a shelf of A1 size, leather-covered large format storage materials

As shown in the above illustrations, Scenario 1 investigates the impact of change in room temperature on Side A, which consists of the leather-covered spines of more than a dozen A4 size books. Scenario 2 investigates the impact of change in room temperature on Side B, which mainly consists of the exposed paper surface of the same books considered in Scenario 1. Scenario 3 considers the leather front cover of a collection of large storage format (A1) under the influence of room temperature change. Scenario 4 considers the paper side of a stack of A1 size collection under the external temperature influence.

Under the flexible set point mechanism, the temperature set point of a room increases or decreases gradually by 2°C over a course of 10 weeks. Here, the model assumes that the 2°C change in temperature set point is translated into a 2°C change in the temperature of room air. Hence, the model essentially studies the impact of a 2°C rise/drop in the surrounding air temperature on a shelf of books.
According to the Newton’s Law of Cooling, when objects are cooled uniformly, its change in temperature can be modelled by an exponential function.\(^{50}\)

\[
\Delta T(t) = \Delta T_0 \cdot e^{-\frac{t}{\tau}}
\]

In this case, \(\Delta T_0\) refers to the initial temperature difference between the surrounding air and the surface of the material. \(\Delta T(t)\) refers to the temperature difference after time \(t\).

The thermal response time of the object in response to an external thermal stress can thus be estimated by \(3\tau\),\(^{51}\) where \(\tau\) is the time constant of the exponential function.

The equation for thermal time constant of the object of study in the four scenarios is

\[
\tau = \frac{\rho C_p V}{U \cdot A}
\]

where \(\rho\) is the density of the book (paper/leather), \(C_p\) is the specific heat capacity of the book (paper/leather), \(V\) is the body volume of the shelf of books, \(U\) refers to the overall heat transfer coefficient, and \(A\) refers to the contact area between the books and the air which varies according to scenarios.

To calculate the overall heat transfer coefficient \(U\), it is assume that only heat conduction and convection contribute to the external thermal stress that acts on the shelf of books in all scenarios. The formula for the overall heat transfer coefficient of a wall/heat exchanger is given as:\(^{52}\)

\[
\frac{1}{U \cdot A} = \frac{1}{h_1 \cdot A_1} + \frac{dx_w}{k \cdot A_w} + \frac{1}{h_2 \cdot A_2}
\]

\(U = \text{the overall heat transfer coefficient (W/m}^2\text{K)}\)
\(A = \text{the contact area for each fluid side (m}^2\text{)}\)
\(k = \text{the thermal conductivity of the material (W/m-K)}\)
\(h = \text{the individual convection heat transfer coefficient for each fluid (W/m}^2\text{K)}\)
\(dx_w = \text{the wall thickness (m)}\)

Though this formula is used for wall or heat exchanger, it can be applied to this model as well. Here the “wall” is equivalent to the leather covers of the books for Sides A and C, and is equivalent to the immediate paper layer beneath Sides B and D. The original equation aims to find the overall heat transfer coefficient for the scenario where there are two kinds of fluid each on one side of a wall. In this model, air is on one side of the leather cover/paper layer and paper is on another. Hence, the “wall thickness” \(dx_w\) is assumed to be 0.2mm.

The only fluid in this case is air, so the term with \(h_2\) and \(A_2\) can be neglected. For each of the four scenarios, there is only one area for consideration. Hence \(A = A_1 = A_w = A_2\)

\(^{50}\) If an object is warmed uniformly, its change in temperature can be modelled by \(\Delta T(t) = \Delta T_0 \cdot (1 - e^{-\frac{t}{\tau}})\)

\(^{51}\) \(3\tau\) signifies that after a time of \(3\tau\), the surface of the material rises/drops in temperature to recover 95% of the external temperature difference, almost reaching equilibrium with the external temperature.

Thus, the formula is simplified into:

\[ U = \frac{1}{\frac{1}{h_{air}} + \frac{dx_w}{k}} \]

Assume the convection heat transfer coefficient for air, \( h_{air} \), to be 10 W/m\(^2\)·K. This is the lowest \( h \) value for air under forced convection.\(^53\) The lower the \( h \) value, the longer the thermal response time. Since the purpose of the model is to show that the rate of temperature change stated in the *flexible set point mechanism* is much longer than that of the slowest thermal response time of the storage materials, a larger value for thermal response time is desired.

Here, four more values are provided to facilitate the calculation for the four scenarios.

**Specific Heat Capacities of Paper and Leather**

\( c_{\text{paper}} = 1.336 \times 10^3 \text{ J/kg·K} \)
\( c_{\text{leather, dry}} = 1.5 \times 10^3 \text{ J/kg·K} \)

**Thermal Conductivities of Paper and Leather**

\( k_{\text{paper}} = 0.05 \text{ W/m·K} \)
\( k_{\text{leather, dry}} = 0.14 \text{ W/m·K} \)

Hence, the overall heat transfer coefficient for each of the four scenarios is calculated to be:

\( U_1 \approx 9.85915 \text{ W/m}^2·\text{K} \)
\( U_2 \approx 9.61538 \text{ W/m}^2·\text{K} \)
\( U_3 \approx 9.85915 \text{ W/m}^2·\text{K} \)
\( U_4 \approx 9.61538 \text{ W/m}^2·\text{K} \)

Finally, the thermal response time, approximated by 3\( \tau \) of each of the four scenarios is calculated as follow:

**Thermal Response Time for Scenario 1**

\[ \tau_1 = \frac{\rho \cdot c_{\text{leather, dry}} \cdot V}{U_1 \cdot A_1} = \frac{m \cdot c_{\text{leather, dry}}}{U_1 \cdot A_1} \]

Side A has a length of 1,000 mm (typical shelf width) and a width of 297 mm (length of an A4 size book).\(^54\) Hence, area of Side A is, \( A_1 = 297 \text{ mm} \times 1,000 \text{ mm} = 0.297 \text{ m}^2 \)

Assume the mass of the shelf of A4 size books to be between 10 to 20 kilograms.

Therefore, the leather-covered Side A of the shelf of A4 size books of mass between 10kg to 20kg in Scenario 1 has a thermal response time, \( \tau_1 \), between 0.8 and 1.7 hours.

**Thermal Response Time for Scenario 2**

\(^53\) The forced convection of air in the University Library is driven by the air-handling units (AHUs). As heating, cooling, humidifying and ventilation systems in the AHUs all contribute to the forced convection of air.

\(^54\) Here the curvature of the book spines is treated as flat surface to ease the calculation.
\[ \tau = \frac{\rho c_{\text{paper}} V}{u A} = \frac{m c_{\text{paper}}}{u A} \]

Side B also has a length of 1,000 mm and a width of 210 mm (width of an A4 size book).\(^{55}\)

Hence, area of Side B is, \(A_2 = 210 \text{ mm} \times 1,000 \text{ mm} = 0.21 \text{ m}^2\)

Hence, Side B (paper) of the shelf of A4 size books in Scenario 2 has a thermal response time, \(\tau_2\), between 1.8 and 3.7 hours.

**Thermal Response Time for Scenario 3**

\[ \tau_3 = \frac{\rho c_{\text{leather, dry}} V}{u_3 A_3} = \frac{m c_{\text{leather, dry}}}{u_3 A_3} \]

Side C has a length of 841 mm and a width of 594 mm (A1 size).\(^{56}\) Hence, area of Side C is, \(A_3 = 594 \text{ mm} \times 841 \text{ mm} \approx 0.5 \text{ m}^2\)

Hence, the leather-covered Side C of the shelf of A1 size books in Scenario 3 has a thermal response time, \(\tau_3\), between 0.8 and 1.7 hours.

**Thermal Response Time for Scenario 4**

\[ \tau_4 = \frac{\rho c_{\text{paper}} V}{u_4 A_4} = \frac{m c_{\text{paper}}}{u_4 A_4} \]

Side D also has a length of 594 mm and a height of approximately 600 mm (which varies with each shelf). Hence, area of Side D is, \(A_4 = 594 \text{ mm} \times 600 \text{ mm} = 0.3564 \text{ m}^2\)

Thus, Side D of the shelf of A1 size books in Scenario 4 has a thermal response time, \(\tau_4\), between 1.1 and 2.2 hours.

According to the model, all the four scenarios show that the storage material in the University Library, regardless of small or large size, leather-covered or not, has a thermal response time of at most 4 hours under an external temperature difference of 2\(^\circ\)C. This means that the surface of the material can reach equilibrium with the originally 2 degree higher/lower external atmosphere within 4 hours.

According to the flexible set point mechanism, the room temperature set point only increases/decreases by 2\(^\circ\)C every 10 weeks. This is 420 times longer than the four-hour thermal response time of a shelf of books. The research findings in Section 4.4 of PAS198:2012 states that:

If major temperature changes are necessary for operational reasons, such as seasonal energy savings, the period of adjustment should be spread over a period several times longer than the slowest response time of collection items.

According to the results of the model and the flexible set point mechanism, the period of adjustment is hundreds of times longer than the thermal response time of the material. Hence, storage materials of paper or leather, which consist the largest part of the Library’s collection,

\(^{55}\) Here, Side B is treated as a flat paper surface and the thickness of leather book covers is neglected to ease the calculation and the same is assumed in Scenario 4.

\(^{56}\) Here, Side B is treated as a flat paper surface and the thickness of leather book covers is neglected to ease the calculation and the same is assumed in Scenario 4.
will unlikely experience any physical damage brought about by the *flexible set point* mechanism.

**Appendix III: Workplace Footprint Tracker League Table**

![Workplace Footprint Tracker League Table](image)
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Appendix IV: List of Rooms Covered in the Real-time Environmental Monitoring

Note: All non-repositories are indicated by red font. All the rest are repositories.

**West Bookstacks:**
- Basement Room 1-5
- Ground Floor Room 1-3
- 1st Floor Room 1-3
- 2nd Floor Room 1-3
- 3rd Floor Room 1-3
- 4th Floor Room 2&3
- 4th Floor Room 1
- West Reading Room

**1934 Scott’s Building (Original Library Building):**
- Ground Floor Glober Case
- Ground Floor Music Bookstore (Music Department)
- Ground Floor North Court
- Ground Floor North Front Room 1 and 2
- Ground Floor South Court
- 1st Floor Main Reading Room
- 1st Floor Map Room A and Map Room B (Map Department)
- 1st Floor Anderson Reading Room
- Between 1st and 2nd Floor Music Bookstore (Music Department)
- Tower 7th Floor
- Tower 12th Floor
- Tower 17th Floor

**North West Corner:**
- Ground Floor Dark Room 1 (Photo&Imaging Service)
- 1st Floor Rare Books Reading Room
- 2nd Floor Bookstore 1 (Microform)
- 3rd Floor Rare Books Reading Room

**South West Corner:**
- 2nd Floor Microfilm Store
- 3rd Floor Official Publication Reading Room
- 4th Floor Microfilm Store

**Aoi Pavillion:**
- Basement Room
- Ground Floor Aoi Reading Room

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57 Both rooms are facing east. Ground Floor North Front Room 1 refers to part of the Ground Floor North Pavilion with windows facing east. Room 2 refers to the room adjacent and to the south of Room 1.
58 Half of the Aoi Basement Bookstacks is open to readers and the other half is closed for storage. However, as the entire basement is subject to the same environmental conditions, the entire room is treated as a repository.
Appendix V – Mapping of the Real-time Measured Environmental Conditions of Areas in the University Library with respect to the Recommended Environmental Design Criteria in the BS5454:2012 and the PD5454:2012

The floor plans of the entire University Library building from the basement to the fourth floor are used for the mapping. The environmental conditions measured in the 44 rooms are rated and marked according to the British Standard 5454 and the Published Document 5454. The signs used for rating and marking are explained below.

- The room monitored satisfies the temperature criteria for the *Frequently Handled Materials* listed under the British Standard 5454. The relative humidity condition satisfies the relative humidity criteria listed under the British Standards 5454.

- The room monitored satisfies the temperature criteria for the *Mixed Archives* listed under the Published Document 5454. The relative humidity condition satisfies the relative humidity criteria listed under the Published Document 5454.

- The room monitored satisfies only the temperature criteria for the *Frequently Handled Materials* listed under the BS5454.

- The room monitored satisfies only the temperature criteria for the *Mixed Archives* listed under the PD5454.

- The room monitored satisfies only the relative humidity criteria for the *Frequently Handled Materials* listed under the BS5454.

- The room monitored satisfies only the relative humidity criteria for the *Mixed Archives* listed under the PD5454.

- The room monitored does NOT satisfy one or more criteria (temperature or relative humidity) under either the PD5454 or the BS5454.

- The room monitored satisfies only the temperature criteria for the *Paper Records Storage* listed under the PD5454.
: The room monitored satisfies only the temperature criteria for the *Cool Storage* (for photographic, audio visual and electronic media) listed under the PD5454.

: The room monitored satisfies both the temperature and relative humidity criteria for the *Reading Room Environment* listed under the PD5454.

: The room monitored satisfies only the temperature criteria for the *Reading Room Environment* listed under the PD5454.

Here is an example of a combination of signs.

: The cross sign shows that the room does not satisfy both guidelines. It satisfies the relative humidity criteria listed under either PD5454 or BS5454. It also satisfies the temperature criteria for the *Paper Records Storage* listed under the PD5454. Essentially, this room satisfies the PD5454 only if it is strictly a *Paper Records Storage* and it does not satisfy the BS5454.
Third Floor:

Fourth Floor
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Tower 7th Floor:

Tower 12th Floor:

Tower 17th Floor:
Appendix VI – Temperature and Relative Humidity Graphs of All Rooms Covered in the Real-time Monitoring

Graphs measured by the four Tinytag Ultra data loggers are first presented. Each Tinytag Ultra creates 16 graphs (temperature and relative humidity) during the eight days of monitoring (July 26th to August 3rd). ¹ Afterwards, graphs measured by the three Tinytag Basic data loggers are presented. As all Tinytag Basics take data only for a day before being reset and placed in another venue, the graphs are grouped in chronological order. Each section “Tinytag Basic [Date]” presents the graphs of the environmental conditions taken by all three Tinytag Basics on the indicated date. Under the each section, graphs with T1 and RH1 in their titles denote the graphs created from the data of the Tinytag Basic One. Similarly, T2&RH2 and T3&RH3 signify the Tinytag Basic Two and Three respectively. Each section for the Tinytag Basics contains 6 graphs, thus eight sections gives a total of 48 graphs. This Appendix presents 112 graphs of temperature and relative humidity conditions monitored by the seven data loggers. It also includes graphs of the benchmarking of the data loggers.

¹ July 29th data is not included as it was a Sunday and the Tinytag Ultras were essentially taking the environmental data of the same room. Also, as each data logger is give half an hour of buffering period before collecting data in a new venue, the transfer of the data loggers from one room to another should be done as early as possible on the subsequent Monday, July 30th. This is to ensure that monitoring that occurs later in the week can complete during the Library’s opening hours for the transfer of the data loggers. Therefore, the three Tinytag Ultras did not run for a full 24-hour period on July 29th to give way to the transfer process on the following Monday.
W.Bookstacks_Grnd flr_Dark Rm
1_T1_8.3 Temperature

W.Bookstacks_Grnd flr_Dark Rm
1_RH1_8.3 Humidity
AOI_Reading Rm_T2_8.3
Temperature

AOI_Reading Rm_RH2_8.3 Humidity
W.Bookstacks_Basement_Rm4_T3_7.26 Temperature

W.Bookstacks_Basement_Rm4_RH3_7.26 Humidity

W.Bookstacks_Grnd_flr_Rm3_T3_7.27 Temperature
Temperature

Humidity

Temperature