THE EFFECT OF RESTORATION INTERVENTIONS ON THE INDOOR CLIMATE OF HISTORIC BUILDINGS: CASE STUDY OF TİRE NECİP PAŞA LIBRARY, İZMİR, TURKEY

A Thesis Submitted to
the Graduate School of Engineering and Sciences of
İzmir Institute of Technology
in Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE

in Architecture

by
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July 2022
İZMİR

ACKNOWLEDGEMENTS

I would never have been able to complete this thesis without the guidance of my advisors, help from friends and support from my family.

I would like to thank my advisors Assoc. Prof. Dr. Zeynep Durmuş Arsan and Prof. Dr. Gülden Gökçen Akkurt for their continuous support, guidance, advices, encouragement, patience, help and knowledge.

I would like to thank my dear friend Umut Özsavaşçı for his many helps.

I would like to thank the administrator of Tire Necip Paşa Library, Ahmet Kılıç and his assistant Mrs. Zozan for their helps and patience during the study. I also would like to thank to the Prime Ministry Directorate General of Foundations, Republic of Turkey for the permission to take measurements in the library and providing important documents.

Besides, I would like to thank IYTE Scientific Research Projects (BAP) committee for providing the funding for indoor and outdoor air pollutant sampling of Tire Necip Paşa Library. Additionally, I would like to thank to Prof. Dr. Eftade Gaga and her assistant Fatma Nur Eraslan from Eskişehir Technical University, Environmental Problems Application and Research Center for providing samplers and carrying out laboratory analyses.

I would like to thank to IYTE Faculty of Architecture, Building Physics Laboratory for providing HOBO U-12 dataloggers, Testo 400 CO_2 logger and DesignBuilder student licence. Besides, I would like to thank to IYTE Department of Energy Systems Engineering for providing HOBO MX1102A CO_2 logger.

Lastly, I would like to thank my father Seçkin Çağırgan and mother Nazan Çağırgan for their unending support, motivation and patience.

ABSTRACT

THE EFFECT OF RESTORATION INTERVENTIONS ON THE INDOOR CLIMATE OF HISTORIC BUILDINGS: CASE STUDY OF TİRE NECİP PAŞA LIBRARY, İZMİR, TURKEY

Libraries are collections of recorded information which can host cultural heritage values that must be protected against mechanical, chemical and biological degradation. To prevent degradations, libraries require stable indoor climates with minimal temperature and relative humidity fluctuations and low concentrations of indoor air pollutants.

Aim of the thesis is to investigate if installing a HVAC system is effective in improving the indoor climate of a historic library as a long-term preventive conservation method on the preservation of paper-based collections. Tire Necip Paşa Library in İzmir was selected as the case building which underwent restoration and a HVAC system integration in 2015. Library's indoor climate was investigated before 2015 which allowed the comparison of pre- and post-restoration periods.

Within the scope of this thesis, library was monitored at five locations between 2019-2021. 2019-2020 monitoring results were compared to pre-restoration monitoring results in terms of degradation risks and ASHRAE Chapter 23 control classes. Pre- and post-restoration indoor climates satisfied A1 and AA control classes, respectively. While there were mechanical and chemical degradation risks before restoration, no risk was observed post-restoration. There was no biological degradation risk during either periods. Additionally air pollutants were sampled during summer and winter of 2020-2021 which showed high SO_2 and NO_2 concentrations. Lastly the BES model of library was prepared and calibrated to investigate if existing HVAC system will continue to provide a stable indoor climate on future. The results of 2050 and 2080 simulations showed that HVAC system will struggle to provide a stable indoor climate.

ÖZET

RESTORASYON MÜDAHALELERİNİN TARİHİ YAPILARIN İÇ MEKAN İKLİMİ ÜZERİNE ETKİSİ: TİRE NECİP PAŞA KÜTÜPHANESİ ALAN ÇALIŞMASI, İZMİR, TÜRKİYE

Kütüphaneler mekanik, kimyasal ve biyolojik bozulmaya karşı korunması gereken kültürel miras değerlerine ev sahipliği yapabilen kayıtlı bilgi koleksiyonlarıdır. Bozulmaları önlemek için kütüphaneler, kısıtlı sıcaklık ve bağıl nem dalgalanmalarına ve düşük iç mekân hava kirleticisi konsantrasyonlarına sahip kararlı iç ortam şartlarına ihtiyaç duyarlar.

Tezin amacı, tarihi bir kütüphanenin iç ortam şartlarını iyileştirmek üzere, uzun vadeli önleyici bir koruma metodu olarak HVAC sistemi kurulmasının etkili olup olmadığının araştırılmasıdır. Çalışma alanı olarak 2015 yılında restorasyonu tamamlanmış ve HVAC sistemi entegre edilmiş İzmir'deki Tire Necip Paşa Kütüphanesi seçilmiştir. Kütüphanenin iç ortam şartlarının 2015'ten önce incelenmiş olması restorasyon öncesi ve sonrası dönemlerin karşılaştırılmasına imkân vermiştir.

Bu tezin kapsamında kütüphane, 2019 ve 2021 yılları arasında beş konumda izlenmiştir. 2019-2020'nin izleme sonuçları, bozulma riskleri ve ASHRAE Bölüm 23 kontrol sınıfları açısından restorasyon öncesi izleme sonuçlarıyla karşılaştırılmıştır. Restorasyon öncesi ve sonrası iç ortam şartları, sırasıyla A1 ve AA kontrol sınıflarını karşılamaktadır. Restorasyondan önce mekanik ve kimyasal bozulma riskleri varken, restorasyon sonrası herhangi bir risk gözlemlenmemiştir. İki dönemde de biyolojik bozulma riski görülmemiştir. Ek olarak 2020-2021'in yaz ve kış sezonlarında hava kirleticiler gözlenmiştir ve yüksek SO_2 ile NO_2 konsantrasyonları tespit edilmiştir. Son olarak mevcut HVAC sisteminin gelecekte de kararlı bir iç mekân iklimi sağlamaya devam edip etmeyeceğini araştırmak üzere kütüphanenin bina enerji simülasyon modeli hazırlanmış ve kalibre edilmiştir. 2050 ve 2080 simulasyon sonuçları HVAC sisteminin kararlı iç ortamı şartları sağlamada zorlanacağını göstermektedir.

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SYMBOLS AND ABBREVIATIONS

A_a	Frequency constant	1/s
BES	Building Energy Simulation	-
CV(RMSE)	Coefficient of variation of the root mean squared error	%
eLM	Equivelant lifetime multiplier	-
E_a	Activation energy	J/mol
k	Reaction rate constant	1/s
LM	Lifetime multiplier	-
LM_x	Lifetime multiplier at point x	-
MBE	Mean bias error	%
MRF	Mould risk factor	-
N	Number of data points	-
ppm	Parts per million	-
ppmv	Parts per million volume	-
R	Gas constant	J/molK
RH	Relative humidity	%
RH_{crit}	Critical relative humidity for porous materials	%
$RH_{crit,w}$	Critical relative humidity for wooden materials	%
RH_x	Relative humidity at point x	%
RMSE	Root mean squared error	%
S	Sum of values	-
T	Temperature	°C
T_m	Monitored temperature	°C
T_{ma}	Average of monitored temperatures	°C
T_s	Simulated temperature	°C
T_x	Temperature at point x	°C
U	Overall heat transfer coefficient	W/m^2K

CHAPTER 1

INTRODUCTION

1.1. Problem Statement

A historic building is defined as a distinguished building with both tangible and intangible heritage values such as architectural and aesthetic ones, connections with historic communities and events, examples of technical progression, characteristics of social history and associations with other buildings with heritage values. All of these values form the identity of a historic building. Conversely, unlike historic buildings, historical buildings may have or not have importance from a historical perspective (Akkurt et al., 2020).

Libraries are defined as collections of books, manuscripts, journals and other sources of recorded information. The library buildings are the places that are specifically built for the purpose of collecting, storing and conserving the recorded information. While providing a healthy indoor climate for the occupants to create a comfortable indoor environment is an essential general design criterion, a library may contain objects with cultural heritage values which require specific stable and balanced indoor climates to conserve them and ensure their longevity. But if library itself is also historic and has cultural heritage values, preserving the library and not doing any harmful interventions which can impact its' heritage value is also as critical as the conservation of cultural objects which are stored in it.

Conservation methods against deterioration of a paper-based collection include the curative (active) and preventive (passive) conservation methods (Bulow, 2002). Curative methods contain direct actions such as stabilization, rebinding and disinfestation. Conversely preventive methods focus on taking measures before deterioration happens such as constant monitoring of the environment, good housekeeping and providing a balanced and appropriate indoor climate via natural ventilation and active systems such as HVAC systems (Bulow, 2002; Atkinson, 2014). Before implementing any measures, a careful analysis of indoor environment should be carried out to implement the correct and necessary measures. Any practices which will negatively impact the indoor environment of the library should be avoided. After the implementation of analyzed measures, they should be further monitored to confirm that they work as intended.

Main indoor environmental conditions that cause the deterioration of a paper-based collection can be listed as inadequate temperatures, humidity, illuminance levels and indoor air pollutants (Fabbri et al., 2014). While historic libraries were generally constructed with the intention of providing adequate indoor environments for their collections via passive architectural solutions as preventive conservation methods, those solutions may be regarded as insufficient in satisfying the higher conservation concerns of contemporary architecture. Providing sustainable design solutions according to modern architectural standards to an ordinary building is not that hard; internal and external insulation, a proper HVAC system, controlling daylight with proper shading design, etc. are various ways of doing so. However, when case building is the historic building, implementing most of these solutions is not possible without harming the heritage value of building, since most of the possible solutions are envelope-based which can have serious negative impacts on the building's identity and cultural significance.

Irreversible deterioration types that are related to thermo-hygrometric parameters of temperature, relative humidity and concentration of indoor air pollutants which libraries try to preserve their paper-based collections from can be grouped into three types as mechanical, chemical and biological degradation. The mechanical degradation can be defined as damage caused by externally applied forces and different fluctuations of T and RH on hourly, daily or weekly basis which can cause degradations to paper such as tearing, swelling, embrittlement and dimension changes. It can cause structural damage which makes having stable library environments with minimal indoor climate changes over time especially essential (Bulow, 2002; Silva et al. 2015). Accordingly, high moisture content coupled with extreme temperatures can cause the chemical degradation such as discoloration on paper and deterioration on text which can be slowed down with preserving paper in indoor environments with low moisture and temperatures (Martens, 2012). The biological degradation, on the other hand, is caused by mold and other microorganisms which can travel to the indoor environments through air transfer by either infiltration, ventilation or human activity and water content. Because of paper's organic composition and hygroscopic properties, it can be regarded as a good nourishment source for those organisms (Bulow, 2002).

To minimize these degradation risks, there are recommended fluctuation limits and intervention methods which are provided by various guidelines and standards that emerged over time due to rising concers in the field of cultural conservation. ASHRAE 2011, EN 2010a, UNI 1999, and PAS 2012 can be named as several guidelines and standards which provide balanced indoor climate parameters (ASHRAE, 2011; EN 15757, 2010; UNI, 1999; PAS, 2012). Among these, ASHRAE Chapter 23 of ASHRAE 2011 provides five climate classes which are AA, A, B, C and D and differ from each other in terms of allowed short-term fluctuations and seasonal adjustments. While degradation risk for different types of materials differ for each climate class, ‘AA’ is considered the climate class with the lowest risk while D is considered the highest. Compared to these standards and guidelines, Turkey does not have a national standard or guideline on the preservation of archival materials.

1.2. Aim of the Study

The aim of the study is to investigate the effectiveness of a HVAC system installation as a long-term preventive conservation method on the preservation of paper-based collections in the historic library. For this purpose, Tire Necip Paşa Library in İzmir, Turkey is chosen as the case building of the study. The first reason of selection is that it is a historic library which underwent the restoration work and HVAC system installation, recently. Secondly, it is the case building of various past researches before the HVAC system installation including:

- Turgay Coşkun’s Master’s thesis, namely “Modelling of Indoor Climate of Historic Libraries for Preventive Conservation of Paper Based Collections” conducted in 2016 by İzmir Institute of Technology, Department of Energy Engineering (Coşkun, 2016).
- Turgay Coşkun’s article, namely "The Effect of Spatial Interventions on Historic Buildings’ Indoor Climate (Case Study: Tire Necip Paşa Library, Izmir-Turkey)." published in 2017 on Energy Procedia (Coşkun et al., 2017).
- Cem Doğan Şahin’s article, namely "Investigation of Indoor Microclimate of Historic Libraries for Preventive Conservation of Manuscripts. Case Study: Tire Necip Paşa Library, İzmir-Turkey." published in 2017 on Sustainable Cities and Society (Şahin et al., 2017).

- Turgay's Coşkun's conference paper, namely "The Effect of Spatial Interventions on Historic Buildings' Indoor Climate (Case Study: Tire Necip Pasa Library, Izmir-Turkey)." published in 2017 on CLIMAMED 2017 conference proceedings (Coşkun et al., 2017).
- Cem Doğan Şahin's conference paper, namely "Humidity Control to Reduce Degradation Risks of Manuscripts in Necip Pasa Library Tire-Izmir, Turkey." published in 2016 on CLIMA 2016 conference proceedings (Şahin et al., 2016).
- Turgay Coşkun's conference paper, namely "Ventilation Strategies for the Preventive Conservation of Manuscripts in Necip Pasa Library, Izmir, Turkey." published in 2016 on IEEES-8 conference proceedings (Coşkun et al., 2016).
- Turgay Coşkun's book chapter, namely "Ventilation Strategies for the Preventive Conservation of Manuscripts in Necip Pasa Library, Izmir-Turkey." published in 2018 on Exergetic, Energetic and Environmental Dimensions (Coşkun et al. 2018).

Therefore, comparing pre- and post-restoration periods in terms of indoor climate is possible. The library currently houses 1754 manuscripts, 2602 books printed in the era of The Ottoman Empire and over 800 books in Latin letters. The degradation risk of this paper-based collection is investigated in terms of mechanical, chemical and biological degradation.

The study was carried out by analysing monitored indoor air temperature and relative humidity data according to various risk analysis methods for each degradation type of paper-based collections. Besides, a general climate risk assessment is conducted according to ASHRAE Chapter 23 (ASHRAE, 2011). Additionally, the concentration of indoor air pollutants are analysed for the periods of summer and winter. Lastly, a calibrated BES model of the library is created with a dynamic building simulation software to investigate the future indoor climate of the library with using generated future climate data.

1.3. Limitations and Assumptions

Limitations and assumptions related to the thesis can be summed up as the difficulties related to monitoring of indoor and outdoor climate, using monitored data in dynamic building simulation software and limitations of the software itself. Firstly, between 01:30 and 13:00 at 31.08.2020, batteries of the all five dataloggers were ran out. To correct this, missing data points were filled with using the last recorded data before batteries ran out which are the monitored T and RH values at 01:30. These periods were not omitted from analyses to prevent discontinuity between finished and started monitored data points.

Secondly, during monitoring period, the HVAC device was turned off for short periods which caused short-term high temperature and relative humidity fluctuations. The reason is the rise of pressure seen in HVAC system's external unit due to it being directly exposed to sunlight and high outdoor air temperatures. This resulted in using monitored data harder for calibration purpose and gave slightly worse calibration results than intended. While these periods could be omitted from calibration process, they were not highly impactful on final calibration results, thus calibrations were done with using entirety of monitored data. From indoor monitoring results of 2020, these periods are assumed to be between 17th and 21st of May, during 20th and 21st of July, during 24th and 25th of July, between 1st and 4th of August and during 1st and 2nd of September.

The limitations due to dynamic building simulation software, i.e. DesignBuilder, is essential because of two reasons. Firstly, it does not contain all types of structural components, thus while modelling the building, building components except doors and windows were custom created by using measurements and on-site observations. Secondly, the main hall of the library was considered 'unoccupied' for occupancy schedule option of simulations even though there were visitors from time to time. Yet, because of the frequency of visits being low and occupation length of visitors being short, these visits were assumed to be unimpactful.

While proper lighting is an important factor on the degradation of a paper-based collection, it is not taken into account during analyses, and is out of the scope of this study.

The office area of Tire Necip Paşa Library has a far less stable indoor climate compared to main hall of the library since it is not constantly regulated by a HVAC system. Because of this reason, office area undoubtedly has an impact on the indoor climate of the main hall due to air infiltration between spaces even though openings between spaces are constantly kept closed. But for the purpose of the thesis, the impact of office area on main hall is assumed to be minimal and thus, investigating the indoor climate of office area and interaction between spaces is out of the scope of this study.

Lastly, according to the aim of the thesis, the preservation conditions of paper-based collection were analyzed. The preservation conditions of ornaments such as calligraphic works on the interior walls of main hall were out of the scope of thesis and thus, were not analyzed.

1.4. Thesis Outline

The thesis consists of five chapters. The first chapter presents the problem statement and aim of the study. The limitations encountered during thesis process and accepted assumptions to work around these limitations are listed. Lastly, the outline of the thesis is explained.

The second chapter contains the literature reviews on similar studies about indoor climate researches on historic buildings such as churches, museums, archives and libraries, degradation risk analysis of paper-based collections and studies which utilize dynamic building simulation software to analyze the impact of various intervention scenarios.

The third chapter presents the case building in detail and the methodology used during the thesis. In this chapter, history of the case library, characteristics and structural details of the building and various schedules such as occupancy, mechanical ventilation, lighting and other electrical devices are given. In terms of methodology, the specifics of monitoring process, indoor climate requirements according to utilized standards, used risk analysis methods for each type of degradation and indoor air pollutant sampling process are explained. In addition, used simulation tool, model creation process and calibration method is described.

The results of general climate risk assessment, degradation risk analyses, indoor air pollutant sampling, model calibration, simulations, simulation results and discussion of the results are presented in the Chapter Four. Lastly, the fifth Chapter contains the interpreted conclusions.

CHAPTER 2

LITERATURE REVIEW

Three study areas of this thesis on preventive conservation methods related to paper-based collections are monitoring the indoor and outdoor climate of the library, controlling the indoor climate and modelling the building for simulation-based analysis purposes. Based on these literature is reviewed in three categories; preventive conservation of paper-based collections, types of degradations risks which they should be preserved against and utilization of simulation models in risk assessment process.

Literature review of the thesis included 51 articles and 16 theses and various reports on the reviewed literature were prepared on the subjects of utilization ways of calibrated models, analyzed indoor pollutants, used standards and measurement devices. 34 of 51 articles investigate the subject of indoor air quality with 26 studying a single case building and 10 studying multiple case buildings. Articles which studied case buildings are shown in Figure 2.1 and categorized according to their research topics, solutions they discussed and if the solution is implemented to the case building or not. 13 of these articles utilize calibrated simulation models in their studies which were prepared in simulation softwares.

Figure 2.2 shows 13 of 51 articles which studied indoor air pollutants in the scope of indoor air quality. These articles are categorized according to the types of studied indoor air pollutants with most common ones being CO_2, NO_2, SO_2, O_3, NH_3, nitric acid, acetic acid, formic acid and particulate matter (PM). 5 of these 13 articles are from Eskişehir Technical University and about the field tests of passive diffusive sampler which is developed by them.

Lastly Figure 2.3 shows 16 theses which are studied in the scope of literature review. Among the investigated theses 4 were Turkish doctorate theses, 2 were foreign doctorate theses, 4 were Turkish master theses and 6 were foreign master theses. Research topics of these theses can be seen below.

	References	Publication Date	Country	Research Topics & Parameters										Energy-Efficient Retrofit Solutions							Solutions' Scope	
				EE	TC	IAQ	ENI	ECI	HV	MD	CD	BD	AT	II	WS	RRWD	IHVAC	IEA	IRES	MI	Theoretical	Practical
Single Case Building	Şahin et al.	2016	Turkey			•			•	•	•	•	•		•		•			•	•	
	Coşkun et al.	2017	Turkey			•			•	•	•	•									•	
	Şahin et al.	2015	Turkey	•	•			•	•				•	•	•	•	•	•	•		•	
	Tronchin et al.	2017	Italy		•	•			•	•										•	•	
	Fabbri et al.	2014	Italy		•	•			•	•	•	•	•							•	•	
	Pereira et al.	2015	Portugal			•			•	•	•										•	
	Luther et al.	2017	Australia	•	•	•				•	•		•		•	•	•					•
	Andretta et al.	2015	Italy			•			•	•	•		•								•	
	Schito et al.	2018	Portugal			•			•		•	•								•	•	
	Schito et al.	2017	Italy						•	•	•	•					•				•	
	Moretti et al.	2020	Italy			•			•	•	•	•				•	•			•	•	
	Muriel et al.	2012	Spain		•	•							•				•			•	•	
	Gonzalez et al.	2016	Spain	•	•	•		•	•	•		•		•	•	•	•				•	
	Silva et al.	2019	Portugal			•			•	•			•							•		•
	Silva et al.	2016	Portugal		•	•			•	•	•	•					•			•	•	
	Magrini et al.	2016	Italy	•			•	•	•												•	
	Odgaard et al.	2017	Denmark			•			•	•	•	•		•								•
	Aste et al.	2018	Italy			•			•	•	•		•							•	•	
	Coşkun et al.	2018	Turkey			•			•		•		•				•				•	
	Pigliautile et al.	2018	Italy		•	•			•					•			•					•
	Ascione et al.	2014	Italy	•	•		•	•	•				•	•	•	•					•	
	Frasca et al.	2019	Italy	•	•	•			•	•			•				•			•	•	
	Kompatscher et al.	2018	Netherlands	•	•	•			•			•					•			•	•	
	Özbalta et al.	2021	Turkey	•				•	•					•		•	•	•	•			
	de Rubeis et al.	2020	Italy	•	•	•			•	•							•				•	
	Coelho et al.	2021	Portugal		•	•			•	•	•	•	•	•	•	•					•	
Multiple Case Buildings	Leissner et al.	2017	Europe	•		•	•		•	•	•	•								•		•
	Haugen et al.	2017	Norway			•	•		•	•	•	•								•		•
	Diulio et al.	2018	Argentina	•		•	•	•	•	•	•										•	
	Maskova et al.	2017	Czech R.			•			•	•	•		•								•	
	Velta et al.	2019	Malta		•												•				•	
	Gonzalez et al.	2020	Spain	•	•	•		•	•	•		•					•	•		•	•	
	Smedemark et al.	2020	Denmark			•			•			•									•	
	Timur et al.	2022	Turkey	•	•			•	•					•	•	•	•			•	•	
	Palomar et al.	2021	Spain			•			•	•	•									•	•	
	Verticchio et al.	2021	Italy			•			•	•	•									•	•	

EE: Energy efficiency, TC: Thermal comfort, IAQ: Indoor air quality, ENI: Environmental impact, ECI: Economic impact, HV: Heritage value, MD: Mechanical degradation, CD: Chemical degradation, BD: Biological degradation, AT: Airtightness, II: Insulation installation , WS: Weather stripping, RRWD: Repairing or replacing of windows and doors, IHVAC: Improving HVAC, IEA: Improving of electrical appliances, IRES: Integration of renewable energy systems, MI: Monitoring installation

Figure 2.1. Reviewed articles which studied on case buildings

References	Method	Measurement D.	Measured Chemical Parameters									
			CO_2	NO_2	SO_2	O_3	NH_3	Nitric A.	Acetic A.	Formic A.	PM	Other
Fabbri et al.	Active	4.5 Months	●									
Pereira et al.	Active	40/34 Days	●								●	
Luther et al.	Active	3 Days	●									
Andretta et al.	Passive	30 Days		●		●						
Maskova et al.	Passive	12 Months		●	●	●	●	●	●	●		
Moretti et al.	Passive	7 Months	●									
Smedemark et al.	Passive	21 Days							●	●		
Palomar et al.	Passive	Unknown			●				●	●		●
Demirel et al.	Passive	1 Day		●		●						●
Can et al.	Passive	7 Days		●		●						●
Üzmez et al.	Passive	250 Days										●
Yurdakul et al.	Passive	5 Days		●	●	●						●
Üzmez et al.	Passive	1 Year		●	●	●						

Figure 2.2. Reviewed articles which studied indoor air pollutants

References	Publication Date	Country	Type	Research Topics
Coşkun et al.	2016	Turkey	Master T.	Analysis of the indoor air quality of a case historic library.
Şahin et al.	2013	Turkey	Master T.	Retrofitting of a historical building via energy simulation software.
Gülhan et al.	2019	Turkey	Master T.	Analysis of natural ventilation scenarios for historical libraries via CFD simulations.
Aksoy et al.	2011	Turkey	Master T.	Investigation of Kur'an-ı Kerim manuscripts in Tire Necip Paşa Library.
Prieto et al.	2018	Czech Rep.	Master T.	Analysis of the indoor air quality of a case pavilion.
Rocha et al.	2017	Portugal	Master T.	Impact of visitors on the indoor air quality of a generic museum room.
Havnes et al.	2019	Norway	Master T.	Thermography analysis of a historic house's envelope.
Pilzer et al.	2016	Netherlands	Master T.	Thermal retrofitting simulations of a historic workshop/office building.
Martens et al.	2012	Netherlands	Master T.	Climate risk assessment in museums with monitored data and simulations.
Bülow et al.	2002	England	Master T.	Climate risk assessment in historical buildings with monitored data.
Yıldırım et al.	2015	Turkey	Doctorate T.	Thermal performance of flat and traditional conic roofs.
Ulu et al.	2018	Turkey	Doctorate T.	Thermal retrofitting simulations of 22 case houses of a historic district.
Yetkin et al.	2020	Turkey	Doctorate T.	Developing a national historic building certification model.
Timur et al.	2019	Turkey	Doctorate T.	Thermal retrofitting simulations of 2 case traditional houses.
Hayati et al.	2017	Sweden	Doctorate T.	Natural ventilation and air infiltration analysis of 5 historical churches.
Coelho et al.	2020	Portugal	Doctorate T.	Impact of future climate change on historical archives and retrofit measures.

Figure 2.3. Reviewed theses

2.1. Preventive Conservation of Paper-Based Collections

Libraries and archives which contain cultural heritage objects such as paper-based collections require balanced and stable indoor climates with minimum temperature and relative humidity fluctuations to preserve them against agents of deterioration. Agents of deterioration which can impact the longevity of a paper-based collection can be listed as high temperatures, relative humidity, concentration of indoor air pollutants and illuminance levels. In terms of preventive conservation of a paper-based collection the most common approach is monitoring and controlling indoor T and RH fluctuations, keeping concentrations of indoor air pollutants such as NO_x, SO_2, O_3, PM and light exposure at a minimum and taking necessary measures as needed depending on the material properties of the collection.

When literature is investigated it is seen that there are two types of library buildings in terms of indoor air control. There are buildings which use active systems such as HVAC systems to control indoor air and buildings with free-floating hygrothermal behaviors which do not use active systems. Mark B. Luther's study on the performance assessment of a school library's HVAC system which compares pre- and post-installation periods (Luther et al., 2018), Cihan Turhan's study which analyzed İzmir National Library in terms of degradation risks and thermal comfort (Turhan et al., 2021), Hugo Entradas Silva's study at a Portuguese museum which tested a sequential process to classify the museum's indoor climate (Silva et al., 2016), Türkan Göksal Özbalta's study on Ahmet Aga Mansion which investigates different retrofit scenarios from a cost-optimal standpoint (Özbalta et al., 2021) and Francesca Frasca's study on Museo Archeologico di Priverno which investigates the effectiveness of a new dynamic temperature control strategy in terms of thermal comfort and HVAC's energy consumption (Frasca et al., 2019) can be given as literature which study a case building with a HVAC system.

Comparatively C.M. Munoz-Gonzalez's study which analyzed thermal comfort and degradation of cultural objects in San Francisco de Asis church (Munoz-Gonzalez et al., 2016), Lamberto Tronchin's study on Malatestiana Library which investigates the impact of different architectural sections on indoor climate (Tronchin et al., 2017), Luisa Dias Pereira's baroque library study which investigates indoor climate parameters including particulate matter (Pereira et al., 2017) and Tullio de Rubeis's historic church study which found that conservation conditions and thermal comfort can be achieved with a complex HVAC system (de Rubeis et al., 2020) investigate case buildings with free-floating hygrothermal behaviors.

Lastly Robert C. Vella's study which investigates thermal comfort of five churches in Malta (Vella et al., 2020), Ludmila Maskova's study which investigates indoor air pollutants and their sources in five archives in Czech Republic (Maskova et al., 2017) and Elena Verticchio's study on the lifetime of paper-based collections of three historic libraries in Italy (Verticchio et al., 2021) are comparative researches which compare buildings with HVAC systems and free-floating hygrothermal behaviors.

When researches conducted in historic libraries of the Mediterranean climate are investigated, it is often seen that free-floating hygrothermal behavior of buildings can be enough to satisfy the base preventive conservation requirements because of buildings generally having high thermal inertia and low airtightness (Fabbri et al., 2014; Andretta et al., 2016). But this can change according to location and building specifications, so a methodic preventive conservation approach is needed to analyze the indoor climate of the building and decide if an intervention is needed or not.

A methodic approach for preventive conservation generally consists of three steps. First step is gathering information on the building's specifications, its' indoor climate and cultural heritage objects contained in the building if there are any. Most common approach in the literature for gathering information on indoor climate of the building is monitoring the indoor climate parameters with dataloggers. Length of the monitoring process is at least a year and gathered indoor data is compared with the outdoor climate data which can be gathered with dataloggers or provided from a weather station. The information on building and its' structure, cultural heritage objects contained in it and objects' storage conditions are gathered via on-site observations, interviews with occupants and official documents if there are any. Second step consists of analyzing the gathered information and monitored data to make risk assessments. Lastly third step consists of discussing possible solutions to eliminate the discovered risks which can reduce the longevity of the building and cultural heritage objects contained in it.

2.2. Types of Degradation Risks

Temperature and moisture are main factors in degradation process of paper since they are impactful on different properties such as weight, diffusivity, strength, dimensions, permanence, etc.. Paper is a material which adsorbs and desorbs moisture in unstable indoor climates while tries to reach equilibrium in steady environments. This process starts when indoor RH is lower or higher than the RH of the material. During this process buffering capacity of paper is an important factor which is the ability of paper to react to and moderate fluctuations in indoor RH. Cyclic humidity changes create moisture content variations in paper which in turn can have damaging effects depending on the buffering property of paper. Also high moisture content for prolonged durations can decrease the overall lifetime of paper and increase the risk of mould germination.

Conversely high indoor temperatures accelerate chemical degradation and temperature fluctuations are as important as fluctuations in humidity in the case of mechanical degradation. High temperatures also provide a suitable environment for mould growth in the case of biological degradation. In the following sub-sections mechanisms of mechanical, chemical and biological degradation and their relation with temperature and moisture content will be explained in-detail.

2.2.1. Mechanical Degradation

Mechanical degradation generally occurs due to physical forces and fluctuations in RH during short periods such as hourly, daily or weekly. Moisture content of organic hygroscopic materials is affected by the fluctuations of indoor T and RH which in turn may cause tearing, swelling, embrittlement and dimensional changes (Silva et al., 2015). Since paper absorbs moisture faster than it releases it, most harmful fluctuations are the ones which take longer than the response time, but shorter than the stress relaxation time. Most paper subjects themselves are generally durable and can survive a daily drop of 25% RH, but ink on paper can become brittle at such lower humidity values (Michalski, 1993). Conversely high moisture content and stress can cause relaxation of paper and related to this, irreversible deformation (Bulow, 2002). Because of these reasons stable indoor climates are utmost important to prevent paper-based collections from mechanical degradation and daily allowed fluctuations by ASHRAE are respectively ±2 K T and ±5% RH (ASHRAE, 2011).

2.2.2. Chemical Degradation

Paper is an organic material which consists cellulose. Cellulose is repeating chains of glucose molecules and because of this molecular structure, it is a material open to chemical degradation in the ways of hydrolytic and oxidative reactions (Library of Congress, 2022). Hydrolytic reactions are related with the presence of moisture content in paper and can cause deterioration of text and discoloration of paper. While moisture transfer qualities of paper products change depending on their production processes and structures, deterioration is slower with lower moisture content and at lower indoor T values. Thus, paper-based collections must be stored in indoor environments with low T and RH values. In the literature it is claimed that 5K decrease in T that is around 20^{o}C doubles the lifetime value of most objects.

Conversely oxidative reactions are related with the presence of various acidic and alkaline pollutants in the environmental air paper product is stored in such as SO_2, NO_2, NO_3, O_3 and H_2S. It is known in the literature that these pollutants repeatedly cut the glucose chains into shorter lenghts and in turn produce even more acids to feed the degradation cycle of paper further. This process is capable of causing damage to paper in the forms of deterioration of text (which also depends on the type of ink used (Liu et al., 2017)) and discoloration of paper (Coşkun, 2016).

To calculate the deterioration rate of materials Equation 2.1 was developed which is named Arrhenius Equation. But Arrhenius Equation does not function at low RH values, so Equation 2.2 was developed by Michalski to calculate the lifetime of paper materials (Michalski, 2003).

$$k = A_a \text{ x } e^{-Ea/(R \text{ x } T)} \quad (2.1)$$

$$LM_x = (50\% / RH_x)^{1.3} \text{ x } e^{Ea/R\ ((1 / (Tx + 273.15)) - (1 / 293.15))} \quad (2.2)$$

Equation 2.2 compares the measured T and RH values as pairs to the set-point environmental conditions of 20°C and 50%. E_a in the equation is activation energy which is 100 J/mol for the cellulose degradation. R on the other hand is gas constant which is 8.314 J/molK. While LM_x is the specific lifetime multiplier at point x, Equation 2.3 is needed to get an equivalent lifetime multiplier (eLM) which covers a wider period of time, generally an annual period. Instead of an arithmetic average, eLM is found out with taking the average of reciprocal values of LM with increasing the impact of values which correspond to worse conditions (Martens, 2012; Sahin et al., 2017; Silva et al., 2016).

$$eLM = 1 / (1/n \text{ x } (\Sigma^n_{x=1} ((50\% / RH_x)^{1.3} \text{ x } e^{Ea/R\ ((1 / (Tx + 273.15)) - (1 / 293.15))})) \quad (2.3)$$

Lifetime multiplier curves in a psychrometric chart can be seen at Figure 2.4. In this chart LM is calculated for another activation energy too which is 70 J/mol and for yellowing of varnish. A LM value below 0.75 is considered highly risky, while a value above 1 is considered low risk. As shown at Figure 2.4 lifetime of materials increases and reaction speed decreases as temperature and relative humidity decreases (Martens, 2012).

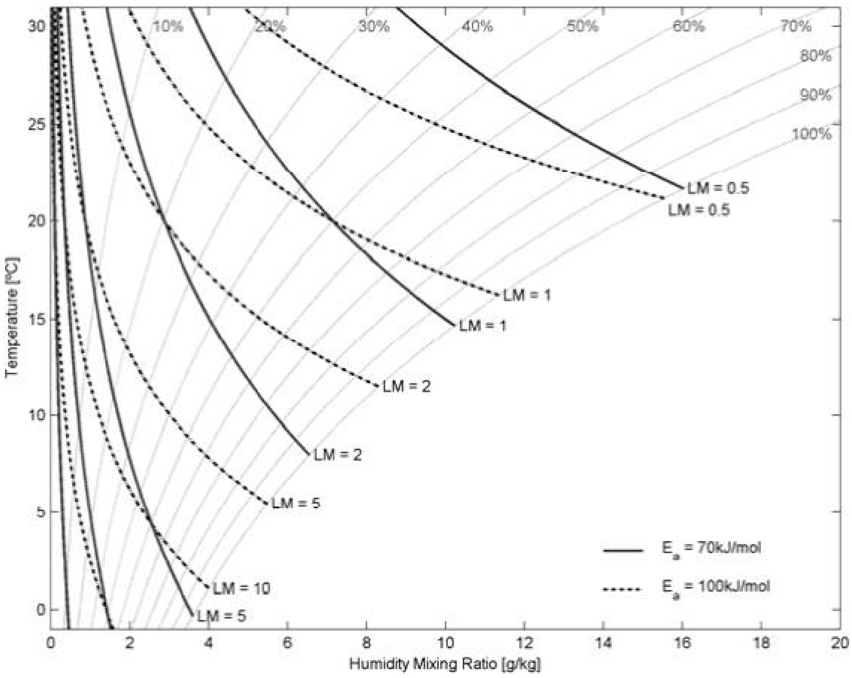


Figure 2.4. Lifetime multiplier curves in a psychrometric chart (Source: Martens, 2012)

2.2.3. Biological Degradation

Microorganisms usually move into the indoor environment from exterior sources via transfer mechanisms such as infiltration, ventilation, human contact or transport of infested items to the interior. When in an environment microorganisms look out for substrates to feed on and germinate. Because of this reason and paper being a good nutrient source due to its' organic structure and hygroscopic qualities, paper is vulnerable to biological degradation. Rate of mould growth depends on the T, RH and substrate parameters of the environment. These parameters being in critical conditions in an indoor environment must be prevented.

In the literature many different mould risk prediction models can be found which take these critical boundary conditions based on thermo-hygrometric parameters into account. Johansson's mould growth indices, fungal index, VIT model, Ayerst and Smith and Hill, ESP-r model, Hens, Sedlbauer and mould germination graph method can be named as some of these methods (Vereecken et al., 2012).

In this thesis Sedlbauer model is used which classifies substrates in 4 classes depending on artifact substrate's suitability for mould growth. For each substrate class an isopleth curve is provided which identifies the germination type and growth rate of mould on artifact. Then measured indoor climate data gets superimposed on these isopleth curves to determine the risk of mould growth. Isopleth diagrams for three different substrate classes for spore germination and mycellium growth can be seen below (Figure 2.5) (Sahin et al., 2017; Sedlbauer, 2001; Sedlbauer et al., 2003; Schito et al., 2017).

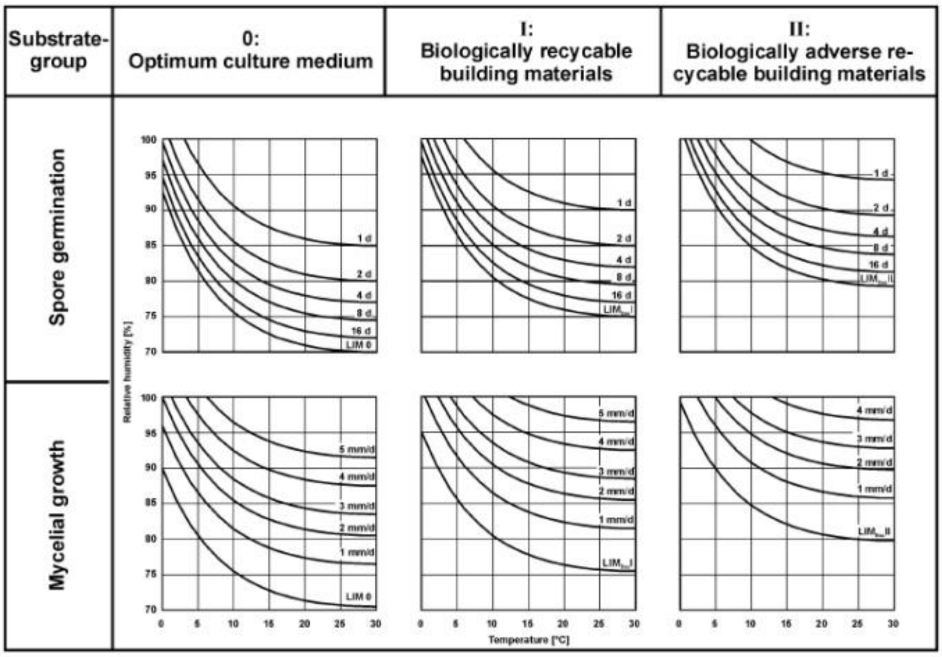


Figure 2.5. Isopleth diagrams for substrate classes of 0, I and II (Source: Sedlbauer et al., 2001)

2.3. Utilization of BES Models and Model Calibration

Building energy simulations are tools which are used to emulate reality from the early design stages of a building to post-construction stage, so aspects which can impact the design of a building such as energy consumption, building's response to different weather conditions, building operation according to different occupancies and schedules and more can be tested and building can be designed according to test results. According to these needs building calibration is a process which is done to fine-tune the BES models, so test results are as close to the reality as possible and right design decisions can be made.

When literature is investigated Lamberto Tronchin's study on Malatestiana Library which use IESVE (Tronchin et al., 2017), Turgay Coşkun's study on Necip Paşa Library, Tullio de Rubeis's study on the Church of Santa Maria Annunziata of Roio and Barış Ali Timur's study on the thermal retrofitting of traditional Muğla dwellings which use DesignBuilder (Coşkun et al., 2017; de Rubeis et al., 2020; Timur et al., 2022) and Francesca Frasca's study on Museo Archeologico di Priverno which use IDA ICE 2017 (Frasca et al., 2019) can be listed as articles which utilize various simulation softwares through their researches.

According to Joseph Andrew Clarke's research which was later revised by T. Agami Reddy, calibration methodologies for BES models can be listed under four categories (Clarke et al., 1993; Reddy et al, 2007):

- Manual calibration methods with iterative approaches.
- Graphical-based calibration methods.
- Calibration based on various test and analysis techniques.
- Automated calibration techniques with analytical and mathematical approaches.

The fourth technique is the method used in this thesis and it is based on analytical and mathematical analysis. It is a technique created by Carroll and Hitchcock in 1993 and is based on validating BES models via dimensionless error indicators. It uses calculated mean bias error (MBE) and the coefficient of variation of the root mean squared error (CV(RMSE)) values to find out the acceptability of the BES model in terms of the accuracy of simulation results it outputs. According to ASHRAE Guideline 14 accepted values for MBE and CV(RMSE) are respectively 10% and 30% (ASHRAE, 2002).

CHAPTER 3

MATERIALS AND METHODS

As explained in the previous chapter, the degradation risk of paper-based collections is investigated with measuring the indoor climate and using measurement results via various risk analysis methods. To collect the required measurement data, monitoring campaigns are carried out for at least a year-long period. The measurement data are also used to calibrate BES models confirming validity of the model; thus accurate results can be gained via simulations. Then, calibrated models are utilized for the investigation of impact of building envelope, mechanical solutions, different natural ventilation scenarios and future climate change on the aspects such as indoor climate and energy consumption of building.

The methodology of the thesis can be grouped into three sections: Individual analyses based on the monitored data of a single a year-long period, comparative analyses between the monitored data of two year-long periods and comparative analyses of air pollutant samplings and CO_2 monitoring between two week-long periods (Figure 3.1). The individual analyses utilize T and RH monitoring results of Tire Necip Paşa Library's interior and exterior spaces which were monitored for two years with dataloggers. Monitored data of the first year was investigated in terms of ASHRAE Chapter 23 control classes and mechanical, chemical and biological degradation risks. The BES model of the library was also prepared in DesignBuilder dynamic building simulation software (DesignBuilder, 2022). The weather data file was created with measured outdoor data in order to use in the simulation model. It was calibrated via measured indoor data according to ASHRAE Guideline 14 (ASHRAE, 2002). Then calibrated model was used to simulate the future indoor climates of the library for the years of 2050 and 2080 with using generated future weather data files. Aim of model creation was to investigate if the indoor climate of the library will continue to be balanced and stable on future.

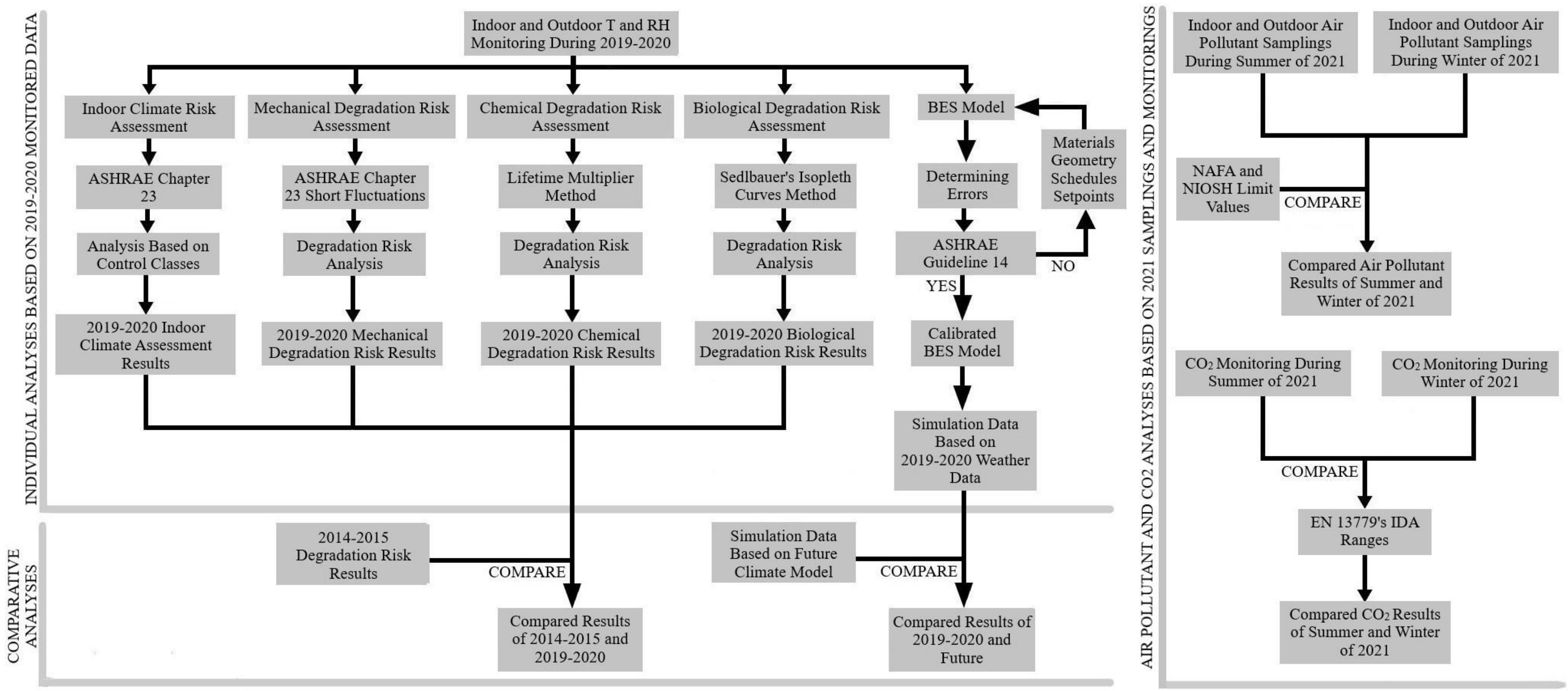


Figure 3.1. Flow diagram of the thesis' methodology

In the second section, ASHRAE Chapter 23 control class assessment results and the mechanical, chemical and biological degradation risk results of 2019-2020 were compared to ones which were found before library underwent a restoration work and HVAC system installation (Figure 3.1). Additionally, results of 2019-2020 were compared to the results of 2049-2050 and 2079-2080 which were found with investigating the simulated indoor climate data of these periods. The weather data files for two future periods were created with morphing the weather data file of 2019-2020 via CCWorldWeatherGen tool (University of Southampton, 2020).

In the third section, indoor and outdoor air pollutants were sampled with passive diffusive samplers and CO_2 concentrations were monitored during summer and winter periods of 2021 to investigate their concentrations depending on different seasons. Then, concentration results were compared to the limit values in the literature.

In this chapter, case building is presented and T and RH monitoring process is explained. Then, ASHRAE Chapter 23's control classes are presented and analysis methods utilized in the thesis for each type of degradation risk are explained. Additionally, air pollutant sampling and CO_2 monitoring processes and how they are analyzed are explained. The chapter concludes with presenting BES tool, BES model of case building, model calibration method and method utilized to carry out future climate simulations.

3.1. Case Building

Library buildings were a special type of building which was built and used for education purposes in The Ottoman Empire. The first standalone library building built in The Ottoman Empire was Köprülü Library of Köprülü Fazıl Mehmet Paşa in 1661 to hold his and his father's manuscript collection. Necip Paşa, Yusuf Ağa, Hafız Ahmet Ağa, Raşid Efendi, Derviş Mehmed Paşa, Yusuf Ziya Paşa, Tekelioğlu and Çaşnigir Libraries can be given as few examples for libraries which were built since then with local materials and construction techniques used in The Ottoman Empire Era (Şahin et al., 2017).

The case historic library of this study is Tire Necip Paşa Library which is located in Tire town of İzmir, Turkey. Tire is located in the Aegean region of Turkey, has a latitude of 38.0861, a longitude of 27.7319 and an elevation of 120 meters (Figure 3.2). The plot of library surrounds with four storey buildings from its' east side, while a public park is located at its' west side. There is a driveway at the south side, while parking lot of Tire Municipality is located at the north side (Figure 3.3). Different facades of the library are given in Figure 3.4.

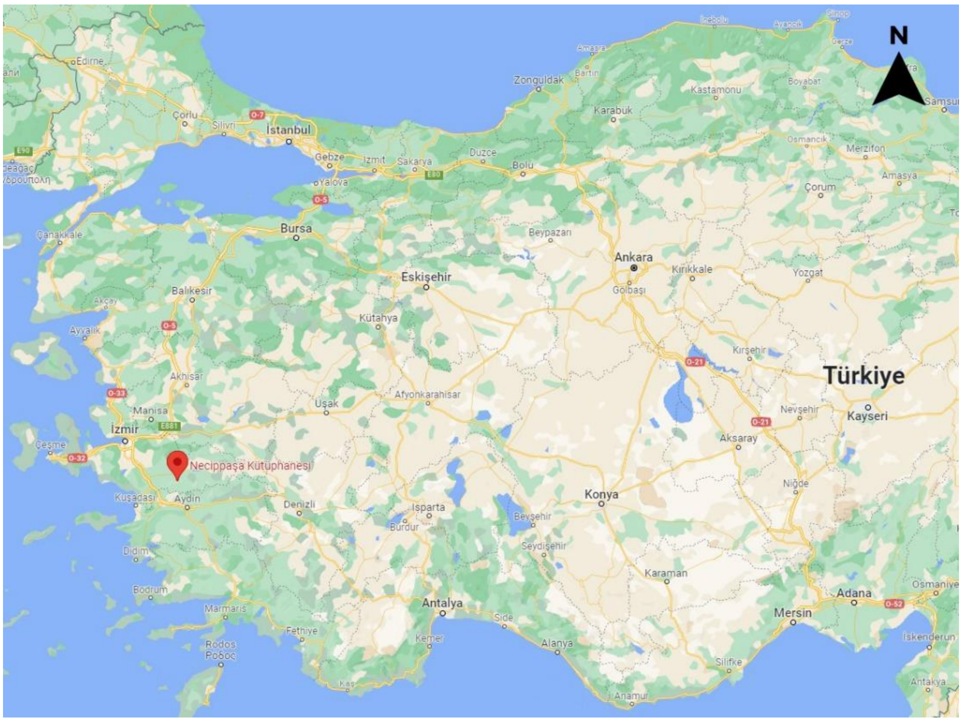


Figure 3.2. Location of Tire, İzmir in Turkey (Source: Google Maps)

Figure 3.3. Aerial photo of Tire Necip Paşa Library (Source: Google Earth, accessed in 23.07.2022)

(a) (b)

(c) (d)

Figure 3.4. Facades of the Tire Necip Paşa Library; south (a), east (b), west (c) and north (d) (Source: Umut Çağırgan archive, 2021)

3.1.1. History of the Building

Tire Necip Paşa Library was built in 1827 by Mehmet Necip Paşa who was a statesman in the Ottoman Empire. Its' construction purpose was to store Mehmet Necip Paşa's own manuscript collection which got changed later with a foundation that he established to financially support the library (Yıldırım, 2004). Today, library houses 1754 manuscripts, 2602 books printed in the era of The Ottoman Empire and over 800 books in Latin letters (Kılıç, 2022).

The original construction of the library was a cubic shaped building covered with a dome roof. This cubic shape's dimensions at floor level are 8.83 m at south, 8.88 m at east, 8.79 at north and 8.90 m at west side. It has a floor area of 78.90 m^2 and the highest point of dome roof is at a height of 12.50 m above ground level. Floor resides at 1.50 m above ground level to protect the paper-based collection against the potential risk of humidity from groundwater. The library had a semi-open entrance area, i.e. the porch, namely *Revak,* at the front (south) side (Figure 3.5). Porch's dimensions were 8.53 m to 2.94 m and had a floor area of 27.17 m^2. Porch was later covered with windows in 1953 and started to be used as office by occupants and working area by visitors (Kılıç, 2022). Office area currently has an area of 24.8 m^2. The indoor space of library, namely main hall, is a single space with the interior dimensions of 6.46 m at south, 6.50 m at east, 6.68 m at north and 6.48 m at west sides. It has an area of 42.7 m^2, a volume of 402.33 m^3 and highest dome point from inside is at a height of 10.71 m above main hall floor. An octagonal shaped cage-like wooden structure (manuscript cage) to the center of main hall was added in 1908 (Kılıç, 2022) (Figure 3.6). Manuscript cage has an area of 9.10 m^2 and a height of 3.78 m. The collection of the library is exhibited in numerous shelves which are located in the manuscript cage and along the three walls of main hall.

Figure 3.5. Tire Necip Paşa Library with its' revak (Source: Kılıç, 2021)

(a) (b)

Figure 3.6. Octagonal manuscript cage before (a) and after (b) restoration (Source: Ekizoğlu, 2012; Umut Çağırgan archive, 2021)

According to the interview carried out with library manager, a basic repair was carried out after 40 years of its' construction in 1827. Then, three more repairs were done in 1940s, 1953 and 1997. Finally, the library underwent the fundamental restoration process in 2015, consisted of a HVAC system installation to the library area and various constructional repair works. The information related to HVAC system installation can be summerized as follows:

- The HVAC system's interior unit is located at the southwest corner of main hall, while exterior unit is located at the northwest corner of the library site.
- The HVAC system is produced by IMAS and is a Tayfun model air conditioner. It has a cooling capacity of 13.1 kW, a heating capacity of 4.5 kW and an air volume of 3200 m^3/h.
- The HVAC system's interior unit has a 0.80 m width, 0.80 m length and 2.35 m height. Conversely, exterior unit has a 0.95 m width, 1.60 m length and 1.60 m height.
- The HVAC system's interior unit is connected to the exterior unit with a pipe that goes through the west wall of main hall.

The restoration items related to construction works can be summerized as follows (Kılıç, 04.12.2020):

- Restoration covered the total height of the library, i.e. up to roof level including dome roof itself. Previously unknown calligraphic works were revealed and these with already known ones were made visually clearer.
- The stone floor of office area was covered with 1.8 cm thick laminated chestnut wood.
- Wooden components of windows were replaced with Ukraine pine and all windows were improved to Isıcam branded double glazing with clear glass.
- Iron lattices at the exterior side and iron shutters at the interior side of main hall windows were painted.
- Old floor bricks of the main hall were replaced with 3 cm thick red brick tiles.
- Manuscript cage's roof was replaced with laminated chestnut wood, and wood components at the sidewalls were varnished.
- Exterior surface of main hall walls were cleared, and voids were filled with Horasan mortar.
- A drainage channel in the garden encircling the main hall of library was excavated.
- Ornaments on the interior surface of dome roof were renewed, but any restoration work were not carried out on the exterior surface.
- Utilization of office area and main hall changed with the restoration process.

After the restoration, manuscripts started to be worked on by the library manager and his assistant via digital copies and are not brought to the outside of main hall except when a digital copy of a manuscript is needed to be created. Visitors started to be able to access manuscripts digitally, but they can no longer examine them physically in office area. Additionally, visitor tours for short durations are started to be allowed. Because of these reasons, it can be said that utilization of main hall and office area changed with the post-restoration.

According to the post-restoration observations of the library manager, windows at the west side of main hall were leaking water to the interior during heavy horizontal rain. Therefore, the weather stripping was renewed on all windows of main hall in June 2022. Additionally, any insect or mould related problems were not observed by library manager since restoration. Lastly, HVAC system's settings were started to get adjusted in 2022 according to seasonal T and RH changes (Kılıç, 05.07.2022).

3.1.2. Local Weather Information of Tire, İzmir

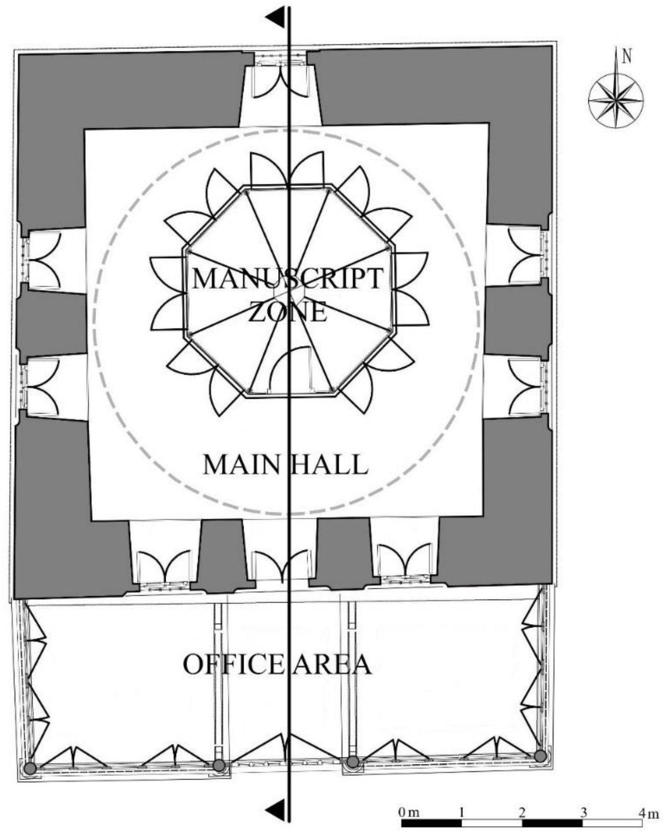
According to Köppen Climate Classification Tire, İzmir's climate is dry-summer subtropical with the subtype of Csa (Hot-summer Mediterranead climate). The annual average temperature is 15.6°C. The warmest month is recorded as July with an average temperature of 26.7°C, while the coldest month is January with an average temperature of 7.8°C (Weatherbase, 2022). The annual average relative humidity is 64.15%. The most humid month is recorded as January with an average relative humidity of 75.97%, while the driest month is recorded as July with an average relative humidity of 51.04% (Weather and Climate, 2022). The average amount of precipitation during a year is 746.8 mm. The month with the most precipitation is recorded as January with an average precipitation of 160 mm, while the month with the least precipitation is recorded as July with an average precipitation of 2.5 mm (Weatherbase, 2022).

The windies month is recorded as July with an average hourly wind speed of 14.32 kmph, while the calmest month is recorded as May with an average hourly wind speed of 10.62 kmph. The dominant wind direction in Tire is the north for 80% of a year with a peak percentage of 71% on 20th of July. The month with the most solar energy incident is July with an average of 8.2 kWh, while the month with the least solar energy incident is December with an average of 2.2 kWh (Weatherspark, 2022). The annual number of sunny days in Tire is 149 on average (Climate-Data, 2022). Tire, İzmir has an elevation of 100 m (Weatherbase, 2022).

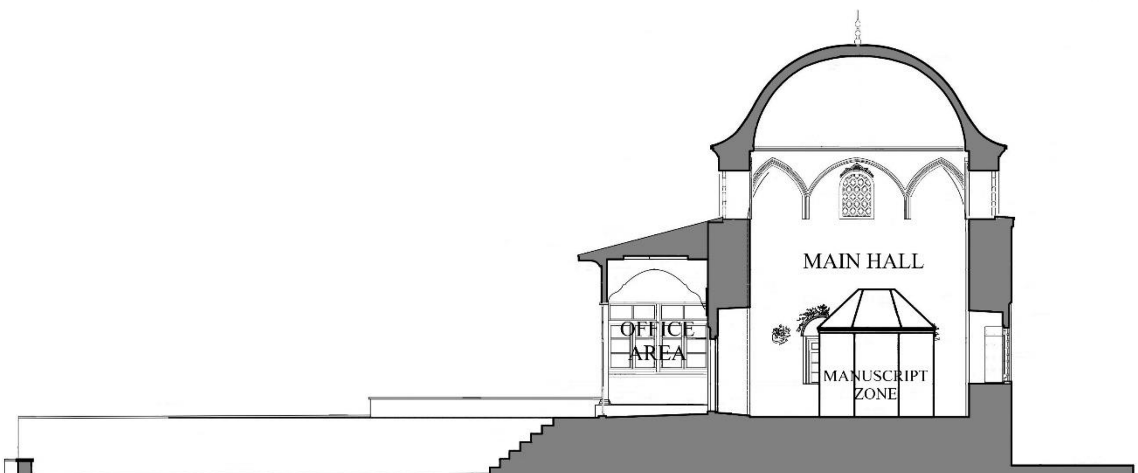
According to the monitored outdoor climate data between December 2019-November 2020 in the garden of Necip Paşa Library, average annual temperature in Tire was 19.86°C. The warmest month was August with an average temperature of 30.96°C, and the coldest month was January with an average temperature of 8.02°C. Conversely, between December 2020-November 2021, average annual temperature was 20.08°C. The warmest month was August with an average temperature of 31.89°C, and the coldest month was January with an average temperature of 11.14°C.

3.1.3. Layout of the Library

The library lies on the north-south axis and consists of three zones, i.e. office area, main hall and manuscript zone. Office area has an interior height of 4.77 m and an area of 24.8 m^2. Main hall has an interior height of 10.71 m and an area of 42.7 m^2. Manuscript zone has an interior height of 3.78 m and an area of 9.1 m^2. These zones are shown in Figure 3.7.



(a)



(b)

Figure 3.7. Plan (a) and section (b) of the library (Source: Archive of Prime Ministry Directorate General of Foundations, 2019)

3.2. Measurements

The basic climate parameters including T and RH of the library were monitored with ten minute intervals for two years from the beginning of December 2019 till the beginning of December 2021. Monitoring was conducted with five HOBO U-12 dataloggers which were located in the manuscript zone (M1), main hall (H1 and H2), office (E1) and by the outbuilding which is at the outside of the library (O1). These are the same locations of the previous monitoring campaign in Turgay Coşkun's Master's thesis (Coşkun, 2016). They were chosen due to be able to make a precise comparison between pre- and post-restoration work. Dataloggers' respective locations on library's site plan and their photographs at each location are given at Figure 3.8 and Figure 3.9, respectively.

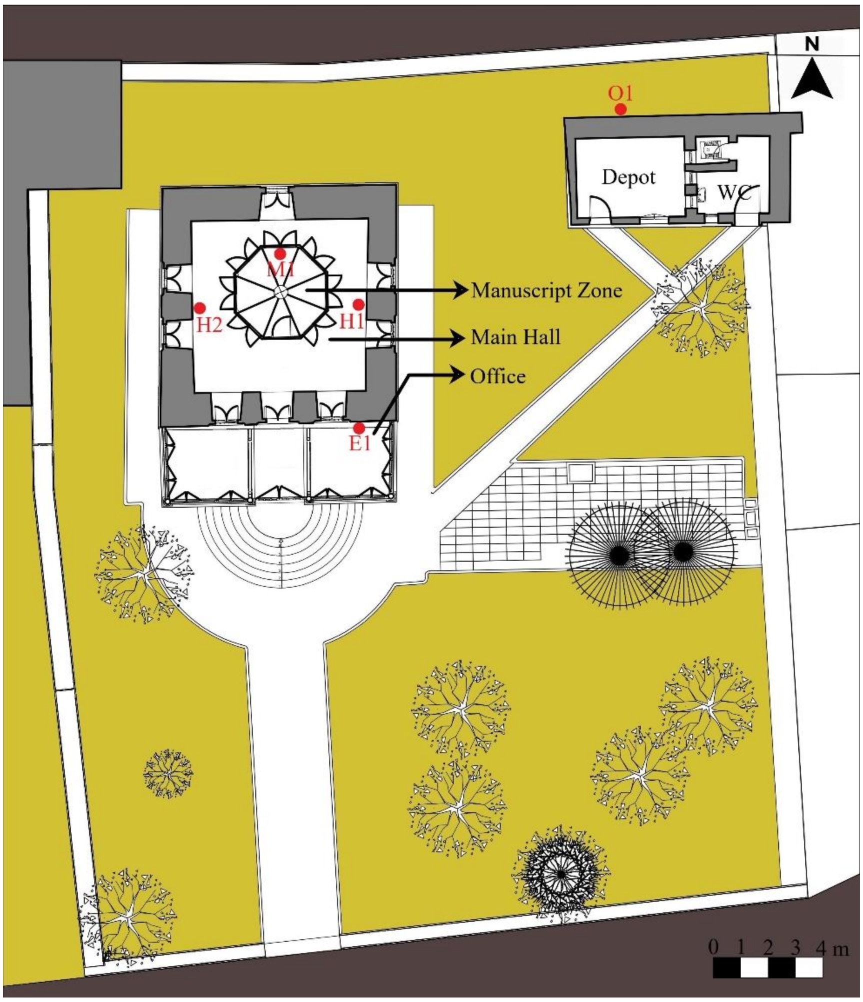


Figure 3.8. Locations of dataloggers on the site plan (Source: Archive of Prime Ministry Directorate General of Foundations, 2019)

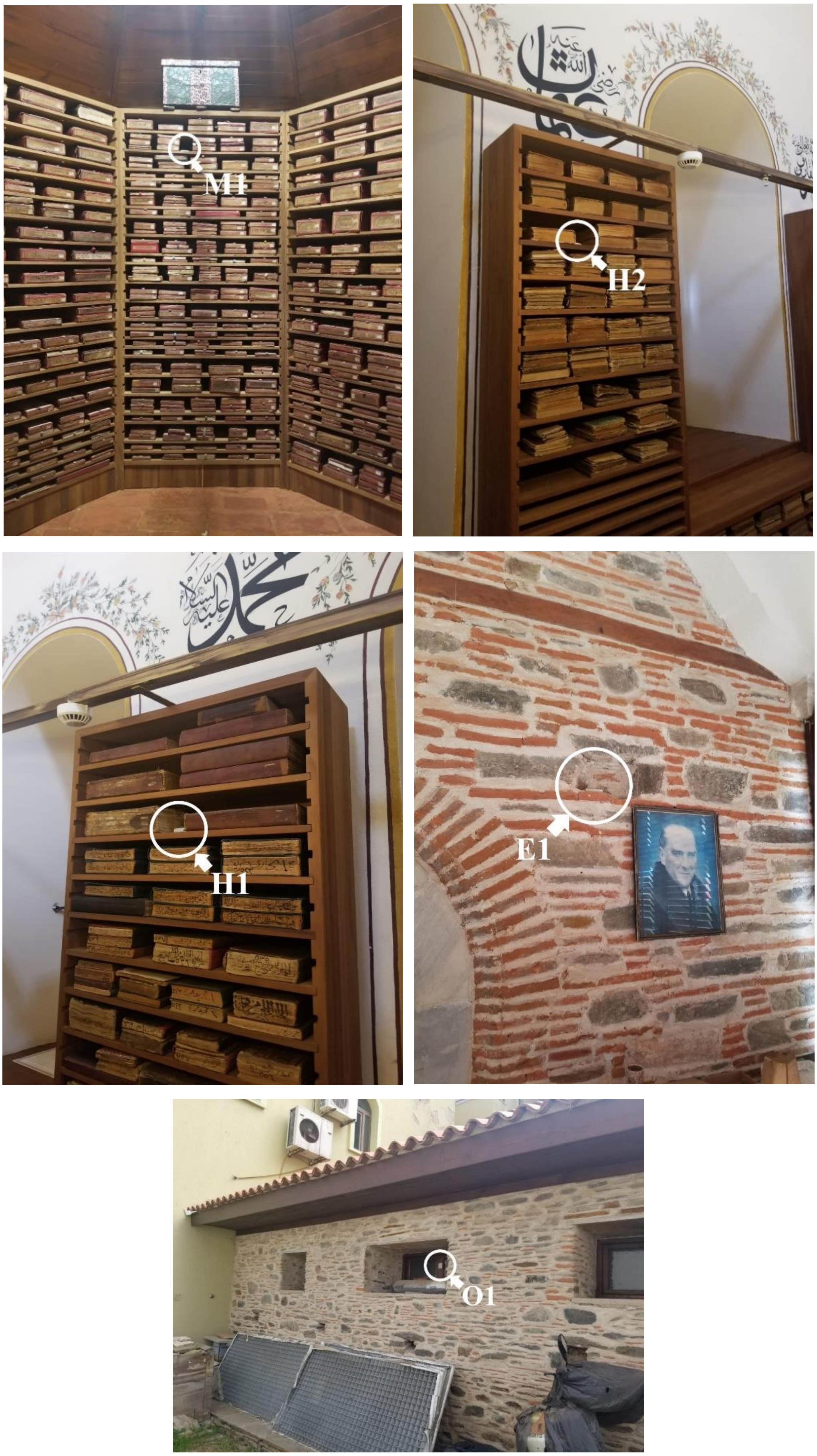


Figure 3.9. Dataloggers at their respective locations

Each datalogger was placed at a height between 196-270 cm to prevent any possible occupant interference. The specifications of datalogger for T and RH measurements can be seen at Table 3.1. Additionally, they have a 64 Kb memory which lasts 105 days if T, RH and light intensity are monitored simultaneously with ten-minute intervals.

Table 3.1. Specifications of HOBO U-12 dataloggers (Source: Onset, 2022)

	T (°C)	RH (%)
Operating Range	-20 to 70	5 to 95
Uncertainty	±0.35	±2.5
Uncertainty Range	0 to 50	10 to 90

During the monitoring campaign data could not be collected between 01:30 and 13:00 at 31.08.2020, because the dataloggers running out of battery. Missing data in data sets were filled with the last measured data before dataloggers' memory ran out to ensure data continuity. While T and RH were measured with ten-minute intervals, their hourly averages were used during analysis process to reduce the number of data points, to be able to compare the monitoring results to simulation results and to be able to analyze results according to standards.

While the main hall was monitored with H1 and H2 dataloggers and the office was monitored with E1 datalogger, data of these dataloggers were not used in the analysis process. Data of H1 and H2 dataloggers were found out to be largely similar to the data of M1 datalogger which was in the manuscript cage at the center of main hall. Therefore, the data of M1 were considered the appropriate one in terms of representing the general indoor climate of library. Besides, it is considered that the measurements of E1 were not required for investigating the degradation risks of library's paper-based collection.

Dataloggers' measurements were assumed to be accurate. The calibration examination of each datalogger in the climate chamber was not carried out before the monitoring campaign of the thesis.

3.3. Indoor Climate Risk Assessment

ASHRAE Chapter 23 (2011) introduces classes of climate control which can be used to assess mechanical, chemical and biological degradation potential of paper-based collections in storage facilities such as libraries, museums, art galleries and archives. A summary of these classes can be seen in Table 3.2.

Table 3.2. Summary of ASHRAE Chapter 23 climate control classes (Source: ASHRAE, 2011)

Type	Set-Point or Annual Average	Class of Control	Short Fluctuations	Seasonal Adjustments
General Museums, Art Galleries, Libraries and Archives	50% RH (or historic annual average for permanent collections), T set between 15 and 25 °C. Note: Rooms intended for loan exhibitions must handle setpoints specified in load agreement.	AA	±5% RH, ±2 K	RH no change, ±5 K
		A (A1)	±5% RH, ±2 K	±10% RH, +5 K, -10 K
		(A2)	±10% RH, ±2 K	RH no change, +5 K, -10 K
		B	±10% RH, ±5 K	±10% RH, +10 K but not above 30 °C, down as low as needed to maintain RH
		C	Within 25-75% annual RH, usually below 25 °C	
		D	Reliably below 75% RH	

ASHRAE Chapter 23 (2011) guideline suggests that the collection objects should be stored either in specific setpoints (15-25 °C and 50% RH) or historic annual average values which should be decided via monitoring results of the indoor environment where they reside in. Therefore, the indoor climate should be kept between specific ranges which may change depending on the seasonal fluctuations. If these requirements are met, objects can be assumed to be protected against various degrees of degradation depending on the class of control in which requirements are fulfilled. If requirements are not fulfilled, major or minor amounts of degradation can be observed depending on the importance of unmet requirement. Therefore, ASHRAE provides five climate control classes to categorise the indoor climates in terms of the preservation conditions of paper-based collections. They are AA, A, B, C and D and each climate control class has different allowed short fluctuation ranges and seasonal adjustment values for both T and RH.

The classes of B, C and D are not taken into account for the purposes of this thesis since their specified T and RH ranges are not enough to satisfy the preservation levels required for the paper-based collections of the case library.

Class AA is the most optimal class of control since no risk of mechanical degradation should be present when requirements are met. According to this class, the short fluctuations of ±2 K in T and ±5% in RH are allowed for weekly, daily or hourly periods. For seasonal basis, the fluctuations of ±5 K in T are allowed, but RH fluctuations are not allowed.

Class A consists two subclasses of A1 and A2. For A1, the short fluctuations are the same with AA, but seasonal fluctuations of ±10% RH are allowed and minimum allowed T drop is 10 K instead of 5 K. Conversely for A2 ±10% RH is allowed for short fluctuations instead of ±5% RH, but seasonal fluctuations are similar to AA's with minimum allowed T drop being 10 K instead of 5 K. Because of wider allowed ranges, a small risk of mechanical degradation is excepted for these classes compared to AA class of control (ASHRAE, 2011).

3.4. Degradation Risk Assessment

The paper-based collection of the case library is investigated according to three types, i.e. mechanical, chemical and biological degradation risk. Each type has individual analysis methods which will be summarized under current sub-chapter. The analyses are conducted with using monitored indoor T and RH data of a year-long period between December 2019-December 2020.

3.4.1. Mechanical Degradation

Mechanical degradation occurs because of significant indoor T and RH fluctuations in short periods of time. Fluctuations in T and RH are investigated with calculating the differences between minimum and maximum monitored T and RH values during these periods of time. These differences are assessed according to allowed short fluctuations of ±2 K T and ±5% RH for AA and A1 and ±2 K T and ±10% RH for A2 control classes of ASHRAE Chapter 23 in Table 3.2 (ASHRAE, 2011). When these daily fluctuation limits are exceeded, there is a risk of mechanical degradation. Higher fluctuation values mean higher risk of mechanical degradation.

3.4.2. Chemical Degradation

To assess the risk of chemical degradation the lifetime multiplier (LM) values are calculated which compares the measured indoor T and RH values as pairs to the set-point environmental conditions of 20°C and 50%. The LM is calculated using Equation 3.1 (Martens, 2012).

$$LM_x = (50\% / RH_x)^{1.3} \text{ x } e^{Ea/R\,((1 / (Tx + 273.15)) - (1 / 293.15))} \quad (3.1)$$

$$eLM = 1 / (1/n \text{ x } (\Sigma^{n}_{x=1}\,((50\% / RH_x)^{1.3} \text{ x } e^{Ea/R\,((1 / (Tx + 273.15)) - (1 / 293.15))}))) \quad (3.2)$$

While LM_x is the specific lifetime multiplier at point x, another equation is needed to get an equivalent lifetime multiplier (eLM) which covers a wider period of time, i.e. the annual period. Instead of an arithmetic average, eLM is found out with taking the average of reciprocal values of LM which increases the impact of values that correspond to worse conditions (Eq. 3.2). E_a in the equation is activation energy which is 100 J/mol for the cellulose degradation. R is gas constant which is 8.314 J/molK.

The LM value between 0.75 and 1.0 corresponds to medium risk. While the high risk of chemical degredation is encountered when LM is below 0.75, an LM value above 1.0 is considered as the low risk (Table 3.3). An eLM value above 2.2 is considered as ideal, while an eLM value below 0.75 is considered as the high risk. The classification of eLM values are given in Table 3.4 (Şahin et al., 2017; Silva et al., 2016).

Table 3.3. Interpretation of LM values (Source: Martens, 2012)

	Low Risk	Medium Risk	High Risk
LM	>1.0	0.75-1.0	<0.75

Table 3.4. Interpretation of eLM values (Source: Silva et al., 2016)

	Ideal	Good	Some Risk	Potential Risk	High Risk
eLM	>2.2	1.7-2.2	1.0-1.7	0.75-1.0	<0.75

3.4.3. Biological Degradation

The risk of biological degradation is evaluated with superimposing the indoor microclimatic conditions onto isopleths, i.e. limit curves as defined in the literature (Sedlbauer, 2001; Sedlbauer et al., 2003; Schito et al., 2017). The isopleths represent the critical RH levels for spores to germinate depending on the indoor T and substrate. Equation 3.3 defines the critical RH level for porous materials used in the building envelope while Equation 3.4 is used for wooden materials. According to a study which determined the atmospheric aerofungi in Izmir via Durhamtrap procedure Cladosporium, Altermaria, Penicillium, Phoma and Aspergillus are the prominent fungi species of this region (Çeter et al., 2009). Equation 3.3 gives the critical RH for the mould specie of Aspergillus Versicolor which has higher germination risks and the lowest isopleths. It also shows good results with a couple of germination isopleths for natural porous materials. Conversely, Equation 3.4 can be used if the material is exposed to the conditions for a long enough time (Vereecken et al., 2012).

$$RH_{crit} = 0.033T^2 - 1.5T + 96 \quad \text{when } T < 30°C \tag{3.3}$$

$$RH_{crit,w} = \begin{cases} -0.00267T^3 + 0.160T^2 - 3.13T + 100 & \text{when } T < 20°C \\ 80 & \text{when } T \geq 20°C \end{cases} \tag{3.4}$$

Using these equations, mould germination is determined with counting the points that exceed the limit curve which refers to the synthetic parameter of mould risk factor (MRF). The risk level of mould growth is assessed according to two determined limit values which are 0.5 and 1.0. An MRF value above 1.0 is considered as the high risk, while an MRF value below 0.5 is considered as the low risk. A classification of MRF values are given in Table 3.5 (Silva et al., 2015).

Table 3.5. Interpretation of MRF values (Source: Silva et al., 2015)

	Low Risk	Medium Risk	High Risk
MRF	<0.5	0.5-1.0	>1.0

In addition to the equations used to find MRF, WUFI-Bio 4.0 simulation software is used to simulate the moisture content of mould spores according to measured T and RH, and to compare results to the critical water content which allows a spore to germinate. If germination is occuring, then subsequent spreading of the infestation can be estimated with using growth curves. Another input which must be selected for the simulation process is the type of substrate. Thus simulations for this thesis are carried out for Sedlbauer's substrate classes of I and II. Substrate class I is used for substrates such as wall paper, plaster boards and bio-degradable building materials, while substrate class II is used for less bio-utilizable substrates like plasters, mineral based materials and wood products. It should be noted that the simulation method of WUFI-Bio is only applicable for interior surfaces, since mould growth on exterior surfaces depend on many more variables such as rain increasing humidity, washing off because of said rain, heating by solar radiation and more (WUFI, 2017).

3.5. Indoor and Outdoor Air Pollutant Sampling

The sampling study of indoor and outdoor air pollutant in the post-restoration period of library is conducted for SO_2, NO_2, O_3 and VOC. The aim of samplings is to find out the concentrations of air pollutants, to investigate if concentrations change depending on the season, and if their concentrations are below the limit values defined by international standards. Samplings are a week long between the dates of 01.07.2021-08.07.2021 for summer and 08.12.2021-15.12.2021 for winter to observe the concentration differences between seasons.

SO_2, NO_2 and O_3 are measured by using four passive diffusive samplers during each period, while VOC is measured by using two passive thermal desorption tubes during each period (Figure 3.10). CO_2 concentrations are also monitored during same periods with a Testo 400 multifunctional logger with CO_2 probe and HOBO MX1102A CO_2 logger devices (Figure 3.11). Indoor and outdoor samplers including four passive diffusive samplers and two passive thermal desorption tubes were placed at P1, and P2, respectively. Testo 400 device was placed at C1, HOBO MX1102A CO_2 logger device was placed at C2 location. Lastly, T and RH data of dataloggers which were previously placed at the locations of H2 and O1 were used to assist the concentration analyses (Figure 3.12).

Figure 3.10. Samplers at their respective locations (left for indoors, right for outdoors)

Figure 3.11. CO_2 loggers at their respective locations (left for indoors, right for outdoors)

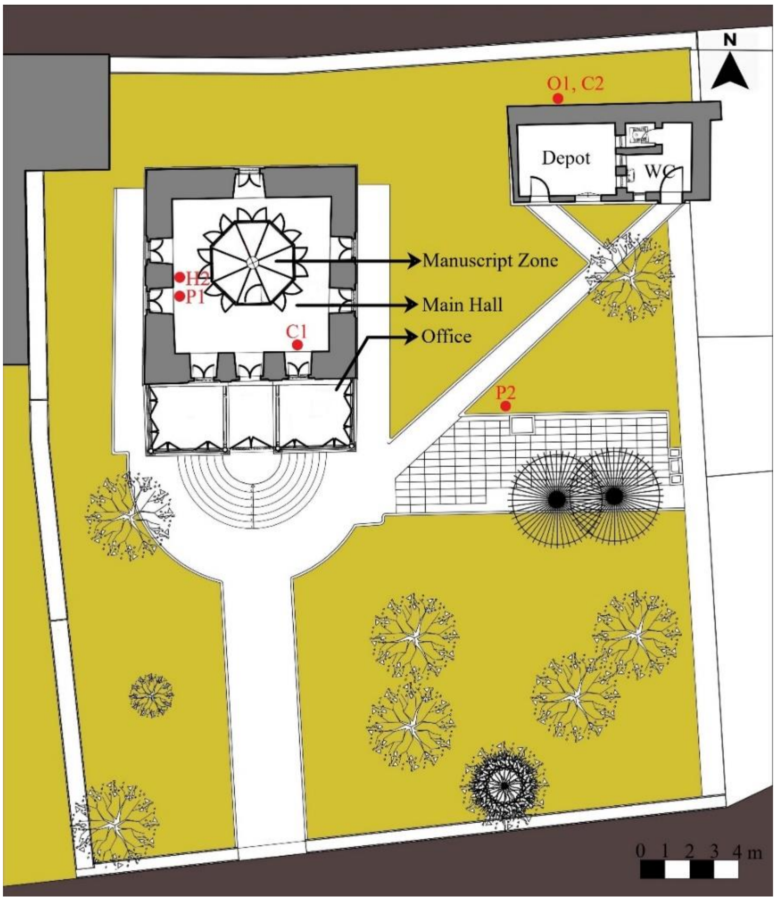


Figure 3.12. Locations of samplers, CO_2 loggers and dataloggers on the site plan (Source: Archive of Prime Ministry Directorate General of Foundations Archive, 2019)

Samplings for SO_2, NO_2, and O_3 were done with passive diffusive samplers which were produced by Eskişehir Technical University, Environmental Problems Application and Research Center (Eskişehir Technical University, 2022). All parts of the sampler are reusable, and made by delrin which is a thermoplastic (ScienceDirect, 2022). They use activated carbon as adsorbent. Adsorbed air pollutants are analyzed by gas chromatography equipped with mass selective detector. The samplers' qualifications are defined in accordance with the European Standards of EN 13528-1 and 13528-2 (Üzmez et al., 2015). Moreover, samplings for VOC are made up of passive thermal desorption tubes by Tenax brand which are stainless steel tubes with brass screw caps.

Sampling process for both summer and winter periods happened with samplers getting shipped by the Eskişehir Technical University, Environmental Problems Application and Research Center. The samplers were sealed and shipped back to Eskişehir Technical University following each sampling campaign. Then, the concentration analyses were performed by the Eskişehir Technical University, Environmental Problems Application and Research Center, and the results were sent back to the author of the thesis.

The results of SO_2, NO_2, and O_3 samplings were analyzed according to recommended limit values provided by the National Air Filtration Association (NAFA, 2016). The recommended exposure limit values of VOC provided by National Institute for Occupational Safety and Health (NIOSH) were considered in the evaluation of VOC measurements (CDC, 2019).

These values are given in 8-hour time weighted averages (TWA). TWA is a method of calculating a worker's daily exposure to hazardous substances. It is averaged to either an 8-hour workday or 40-hour week along with the average levels of exposure and the time spent in that area (Safeopedia, 2021). The concentration results of the sampling were converted to TWA according to Equation 3.5.

Concentration Result x Sampling Duration in Hours / 8 = Concentration in TWA (3.5)

Lastly, the results of CO_2 monitoring were analyzed according to IDA (indoor air) ranges provided by EN 13779 (EN 13779, 2006). There are four IDA categories which categorize indoor air quality from high to low according to majority of CO_2 concentrations observed in the indoor environment. The IDA categories are not specific to libraries and can be used to categorise the indoor air of any non-residential building. These categories are given in Table 3.6.

Table 3.6. Classification of IDA categories according to CO_2 concentration ranges (Source: EN, 2006)

Category	Description	CO_2 Level Range (ppm)
IDA 1	High indoor air quality	0-400
IDA 2	Medium indoor air quality	400-600
IDA 3	Moderate indoor air quality	600-1000
IDA 4	Low indoor air quality	>1000

3.6. BES Tool

DesignBuilder ver. 6.1.8. dynamic simulation software is used in the thesis to create the simulation model of the library and to run simulations. DesignBuilder uses EnergyPlus to do simulations which is a whole building energy simulation engine that is used to model the energy consumption and water usage of the buildings (EnergyPlus, 2022).

DesignBuilder is a dynamic building simulation software which has a user-friendly interface and highly customizable building specifics such as occupancy and operation schedules, heating and cooling, lighting, domestic water usage, equipment loads and building materials. While the software has its' own libraries for HVAC systems, common building materials, etc., it also allows user to create custom systems and materials if they do not exist in the software's libraries. It also includes different modules which lets user to do calculations about the building such as suitability to LEED, cost estimations and computational fluid dynamics (CFD) calculations (DesignBuilder, 2022).

3.7. BES Model

After obtaining plans and sections of the case building and building site as AutoCAD files from Prime Ministry Directorate General of Foundations, Republic of Turkey, floor plan was simplified and converted to .dxf format. Then to create the BES model, .dxf file was imported to DesignBuilder simulation software and building was modelled with taking floor plan as a basis. Office area, library area and manuscript zone were modelled as separate blocks. Then top of the office area was covered with a triangular roof and library area was covered with a dome roof. Modelling finished with adding doors and windows. Figure 3.13 shows the interior of the library model, while Figure 3.14 shows finished BES model of the case library with its' surroundings.

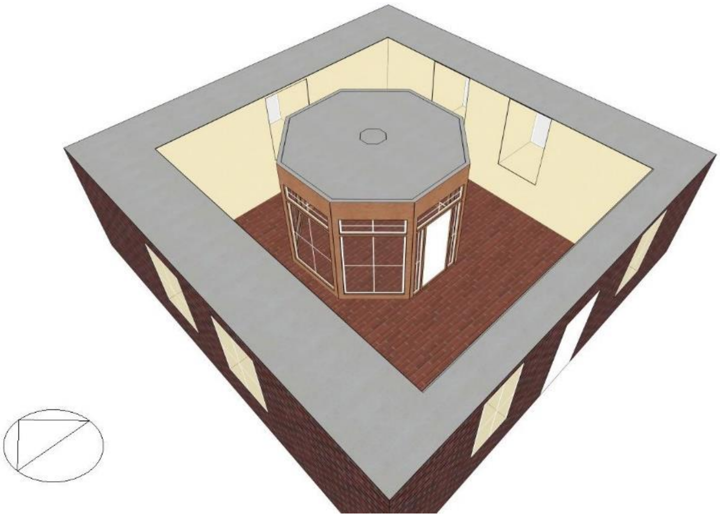
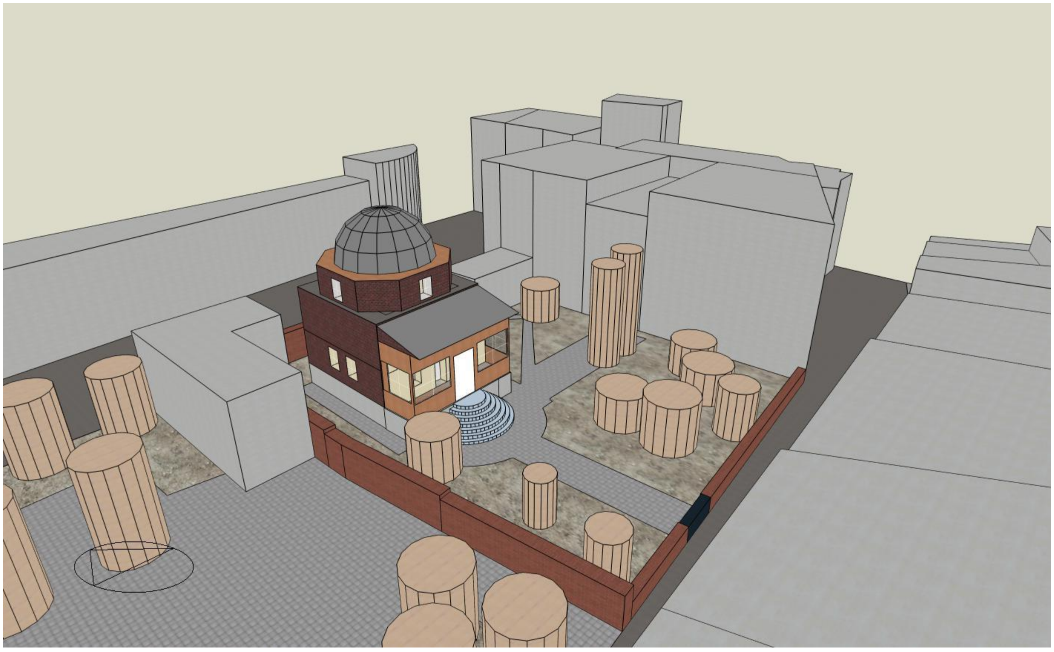


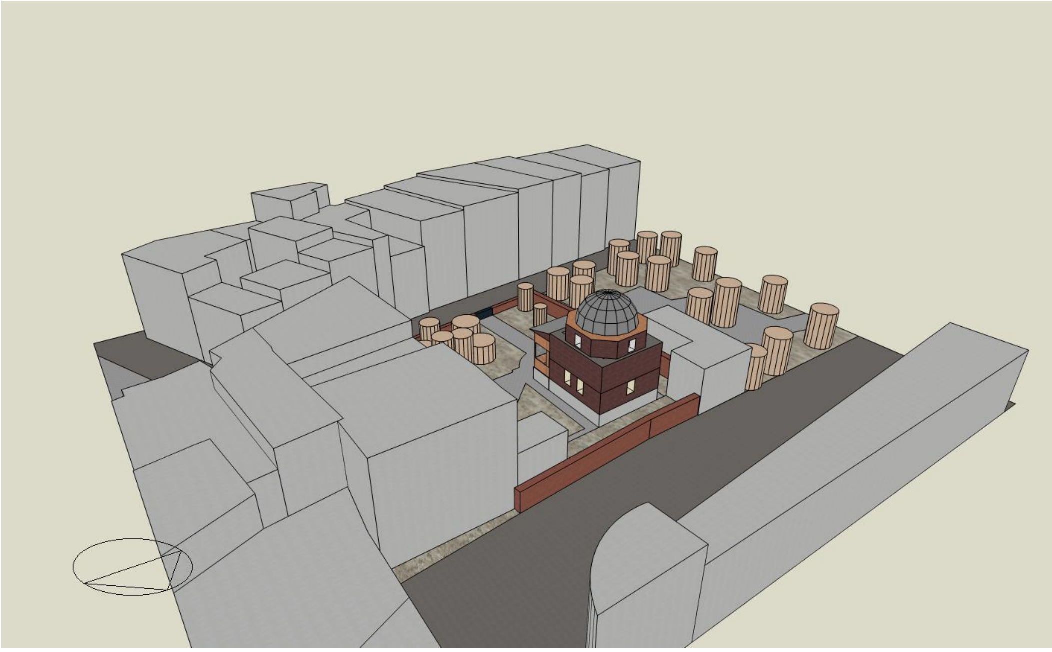
Figure 3.13. Interior view of the case library's model



(a)

Figure 3.14. Exterior views of the BES model from southwest (a) and northeast (b)

(cont. on next page)



(b)

Figure 3.14 (cont.)

All parts of the building were modelled as separate building blocks with their own zones, schedules and component materials Zones were modelled and structural components (walls, floors and roofs) were custom-created according to the material information provided in AutoCAD plans and sections. Conversely schedules related to occupancy, lighting, equipment and HVAC system were decided according to information gathered during on-site observations and provided by library manager. Compared to the blocks of case library, all surrounding blocks (different buildings, trees and ground) were modelled as component blocks with site as their level and a maximum transmittance of 0.00. Surrounding buildings' heights change between 2-4 storeys.

3.7.1. Structural Components

Table 3.7, 3.8 and 3.9 contains the material information of structural components of the library. Component materials were chosen according to information provided in Turgay Coşkun's thesis (Coşkun, 2016) and components were created from the materials which are found in DesignBuilder's material library. Layer thicknesses were decided according to drawings in AutoCAD files. Density, conductivity and specific heat information in these tables are information provided by DesignBuilder itself, while U-value of components are calculated by DesignBuilder according to components' layers.

3.7.1.1. Walls

The external walls of the main hall have a non-homogeneous composition of rubble stone and brick with Khorasan mortar used as a binding material. Thickness of walls gradually change between 1.05-1.25 m, but for the BES model all walls are accepted to be 1.25 m and have a composition of 50% stone and 50% brick. Walls of manuscript zone and office area are composed of wooden framing (Figure 3.16). Specifications of walls can be seen in Table 3.7, while sections of walls are given in Figure 3.15.

Table 3.7. Specifications of walls (Source: DesignBuilder, 2022)

BUILDING COMPONENT	U - VALUE (W/m2K)	LAYERS	THICKNESS (m)
Main Hall Wall	0.797	Brickwork, Outer	0.31
		Stone	0.62
		Brickwork, Inner	0.31
		Gypsum Plastering	0.015
Manuscript Zone Partition	1.273	Wood, Soft	0.08
Office Area Wall	1.436	Oak, Radial	0.10

BUILDING COMPONENT	LAYERS	DENSITY (kg/m3)	CONDUCTIVITY (W/mK)	SPECIFIC HEAT (J/kgK)
Main Hall Wall	Brickwork, Outer	1700	0.84	800
	Stone	2880	3.49	840
	Brickwork, Inner	1700	0.62	800
	Gypsum Plastering	1000	0.40	1000
Manuscript Zone Partition	Wood, Soft	630	0.13	2760
Office Area Wall	Oak, Radial	700	0.19	2390

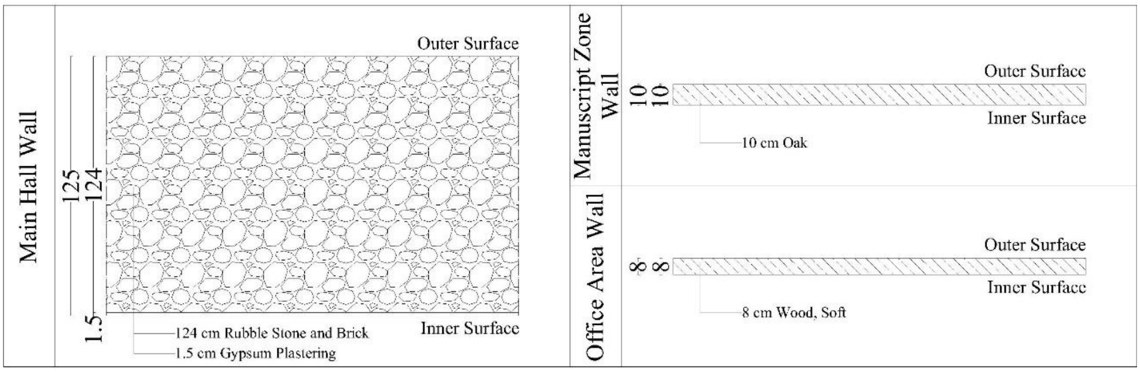


Figure 3.15. Sections of main hall, manuscript zone and office area wall

(a) (b)

Figure 3.16. External walls of main hall (a) and office area (b) (Source: Umut Çağırgan archive, 2021)

3.7.1.2. Floors and Roofs

Innermost layer of the main hall floor is cast concrete except the section which manuscript cage resides on which is paviour brick. Conversely office area has a flooring composed of marble (Figure 3.17). Specifications of floors can be seen in Table 3.8, while their sections are given in Figure 3.18.

Table 3.8. Specifications of floors (Source: DesignBuilder, 2022)

BUILDING COMPONENT	U - VALUE (W/m2K)	LAYERS	THICKNESS (m)
Main Hall Floor	1.323	Brick, Tile	0.30
		Floor Screed	0.07
Manuscript Zone Floor	1.443	Brick, Paviour	0.13
		Floor Screed	0.07
		Cast Concrete	0.20
Office Area Floor	1.970	Chestnut	0.018
		Marble	0.05
		Floor Screed	0.07

BUILDING COMPONENT	LAYERS	DENSITY (kg/m3)	CONDUCTIVITY (W/mK)	SPECIFIC HEAT (J/kgK)
Main Hall Floor	Brick, Tile	1890	0.80	880
	Floor Screed	1200	0.41	840
Manuscript Zone Floor	Brick, Paviour	2000	0.96	840
	Floor Screed	1200	0.41	840
	Cast Concrete	2000	1.13	1000
Office Area Floor	Chestnut	720	0.16	1260
	Marble	2800	3.50	1000
	Floor Screed	1200	0.41	840

(a) (b)

Figure 3.17. Floors of manuscript zone (a) and main hall (b) (Source: Umut Çağırgan archive, 2021)

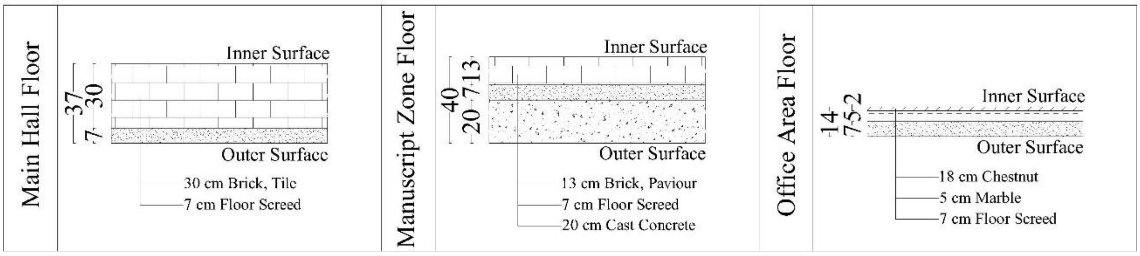


Figure 3.18. Sections of main hall, manuscript zone and office area floors

A lead-covered dome roof covers the main hall of the library, while office area has a lead-covered hip roof. Specifications of roofs can be seen in Table 3.9, while sections of roofs are given in Figure 3.19.

Table 3.9. Specifications of roofs (Source: DesignBuilder, 2022) (cont. on next page)

BUILDING COMPONENT	U - VALUE (W/m2K)	LAYERS	THICKNESS (m)
Main Hall Dome Roof	1.939	Lead	0.03
		Brick	0.25
		Cement Plaster	0.02
Office Area Baghdadi Ceiling	3.252	Lead	0.03
		Brick	0.10
		Cement Plaster	0.02

Table 3.9 (cont.)

BUILDING COMPONENT	LAYERS	DENSITY (kg/m3)	CONDUCTIVITY (W/mK)	SPECIFIC HEAT (J/kgK)
Main Hall Dome Roof	Lead	11300	35.00	130
	Brick	1920	0.72	840
	Cement Plaster	1760	0.72	840
Office Area Baghdadi Ceiling	Lead	11300	35.00	130
	Brick	1920	0.72	840
	Cement Plaster	1760	0.72	840

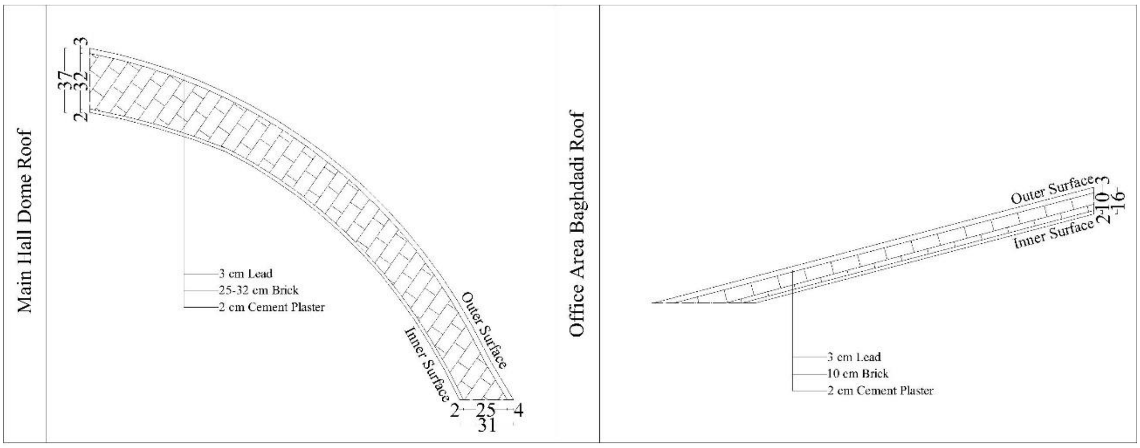


Figure 3.19. Sections of main hall’s dome roof and office area’s baghdadi ceiling (Source: Archive of Prime Ministry Directorate General of Foundations, 2019)

3.7.1.3. Windows and Doors

Main hall of the library consists seven windows at the floor level and four smaller windows at the partition wall below the dome roof. Conversely office area is completely surrounded by windows. After the restoration all windows became windows with double glazing and pine wood frames (Figure 3.20).

(a) (b)

Figure 3.20. Windows of main hall (a) and office area (b) (Source: Umut Çağırgan archive, 2021)

Three wooden doors exist in the library which are respectively manuscript zone's, main hall's and office area's doors. While all doors are wooden, main hall's door has metal layers and office area's door has double glazing (Figure 3.21) Specifications of windows and doors can be seen in Table 3.10, while sections are given in Figure 3.22.

Table 3.10. Specifications of windows and doors (Source: DesignBuilder, 2022)

BUILDING COMPONENT	U - VALUE (W/m2K)	LAYERS	THICKNESS (m)
Double Glazing	3.159	Clear Glass	0.003
		Air	0.006
		Clear Glass	0.003
Main Hall Door	1.834	Steel	0.01
		Wood, Hard	0.06
		Steel	0.01
Office Area Door	2.309	Oak	0.05

BUILDING COMPONENT	LAYERS	DENSITY (kg/m3)	CONDUCTIVITY (W/mK)	SPECIFIC HEAT (J/kgK)
Double Glazing	Clear Glass	not specified	0.90	not specified
	Air	not specified	not specified	not specified
	Clear Glass	not specified	0.90	not specified
Main Hall Door	Steel	7800	50.00	450
	Wood, Hard	720	0.16	1260
	Steel	7800	50.00	450
Office Area Door	Oak	700	0.19	2390

(a) (b)

Figure 3.21. Doors of office area (a) and main hall (b) (Source: Umut Çağırgan archive, 2021)

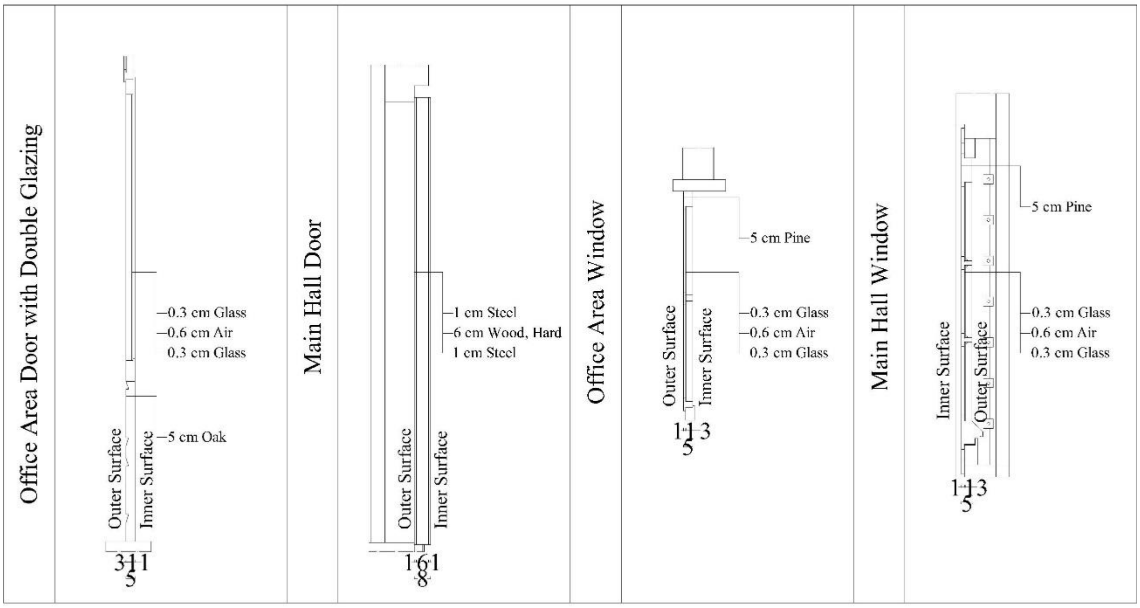


Figure 3.22. Sections of office area door, main hall door, office area windows and main hall windows (Source: Archive of Prime Ministry Directorate General of Foundations, 2019)

3.7.2. Schedules

To get accurate simulation results, DesignBuilder software requires schedule data as an input. Schedules which increase the accuracy of a model and DesignBuilder uses include occupancy, heating, cooling and ventilation, lighting and equipment usage. Schedules for the model which the thesis uses were estimated and prepared according to the information acquired from library manager.

3.7.2.1. Occupancy Schedule

Occupants of the library are library manager, his assistant and a security guard. For the entirety of working hours library manager and his assistant use office area, while security guard is using a security cabin at the entrance of the library's garden. Office area of the library is occupied between 08:30-17:30 from Monday to Friday in a week and it is not occupied during weekends.

Main hall of the library is not occupied except during visitor tours which happen rarely or when occupants need to retrieve a manuscript which takes a very short time. Because of this reason, main hall is considered unoccupied in terms of simulation schedule.

3.7.2.2. Heating, Cooling and Ventilation Schedule

Office area is heated and cooled with a tower type air conditioner as needed and accepted to be always on during working hours of summer and winter seasons. Main hall is heated and cooled with a unitary heat pump which is always on to maintain the stable indoor climate for preservation purposes. Unitary heat pump has an interior unit and an exterior unit which is located at the west side of the library (Figure 3.23). Library is never naturally ventilated.

(a) (b)

Figure 3.23. HVAC systems in office area (a) and main hall (b) (Source: Umut Çağırgan archive, 2021)

3.7.2.3. Equipment Schedules and Lighting

In the main hall there is not any electrical equipment. Conversely office area has two computers which are on during working hours and a security camera system which is always on. Lighting of main hall is always off. While lighting of office area is used when it is dim due to bad weather conditions, it is also accepted to be always off for BES model.

3.8. Calibration of the Model

Model was calibrated according to ASHRAE Guideline 14 (ASHRAE, 2002). The ASHRAE provides us with two ways of determining errors of building models with comparing the gathered hourly indoor T data through monitoring and simulations which are root mean square error (RMSE) (Eq. 3.6) and mean bias error (MBE) (Eq. 3.7).

$$RMSE\ (\%) = (100/T_{ma}) * [1 / N * (S(T_s - T_m)^2)]^{1/2} \quad (3.6)$$

$$MBE\ (\%) = (100/T_{ma}) * [S(T_s - T_m)] / N \quad (3.7)$$

While hourly indoor temperature data is put in equations, RMSE results must be below 30% and MBE results must be below 10% for the model to be accurate (ASHRAE, 2002). Calibrations for the thesis' BES model were done for the period between 01.01.20 at 12:00 AM and 01.01.2021 at 12:00 AM which corresponds to the monitoring period and for library area.

To calibrate the final library model two annual simulations were run with changing heating, heating setback, cooling and cooling setback temperature values of HVAC system. For both simulations humidification and dehumidification was turned on. Temperature and humidification values for each simulation can be seen on Table 3.11. These values were chosen to receive indoor climate results as close as possible to targeted air temperature and relative humidity values which respectively are 18 ºC and 50-60% RH.

Table 3.11. HVAC values for each calibration simulation

	Simulation_1	Simulation_2
Heating	17.50	18.00
Heating Setback	13.50	14.00
Cooling	18.50	18.00
Cooling Setback	20.50	20.00
RH Humidification Setback	50.00	50.00
RH Dehumidification Setback	60.00	60.00
Humidification	On	On
Dehumidification	On	On

3.9. Simulations

Aim of the simulations were to find out whether the existing set conditions of HVAC system in the main hall of library will continue to provide a balanced indoor climate to the library on future in terms of the preservation of the paper-based collection of the library, or not. For this purpose future climate scenarios were used to create future weather files and simulations were run with using these weather files to simulate the library's future indoor climate.

In this thesis Climate Change World Weather File Generator tool (CCWorldWeatherGen) was used to create future weather files. CCWorldWeatherGen is a Microsoft Excel based tool which is created by University of Southampton and morphs present-day .epw-formatted weather files to future weather files. Future weather files for the years of 2050 and 2080 can be created and tool uses Intergovernmental Panel on Climate Change's (IPCC) Third Assessment Report's model summary data of HadCM3 A2 (University of Southampton, 2020). A2 is a very un-favourable future scenario which pictures a highly heterogeneous world with continuous global population increase and regionally oriented, fragmented and slow economic growth. A2 storyline predicts an atmospheric CO_2 concentration of over 800 ppmv by the year of 2100 (IPCC, 2019).

Two simulations were done in DesignBuilder software with using final calibrated model and generated weather files of 2050 and 2080 to simulate the future indoor climate of Tire Necip Paşa Library's manuscript zone. Then simulated T and RH data of these two periods were analyzed and compared to the monitored data of December 2019-November 2020 in terms of climate control classes of ASHRAE Chapter 23 and degradation risks.

CHAPTER 4

RESULTS AND DISCUSSION

The main aim of the thesis is assessing the indoor climate of the library's main hall to find out if the paper-based collection in the library is under the risk of any type of degradation after the restoration work when library underwent in 2015. Therefore, various analyses were carried out and the results of these analyses are presented in this chapter.

The results which are gathered with utilizing the monitored T and RH parameters of 2014-2015 and 2019-2021 are presented first and include comparative monitoring results, asssessment results for AA, A1 and A2 climate control classes of ASHRAE Chapter 23 and results of mechanical, chemical and biological degradation risk analyses. Afterwards, BES model calibration results, air pollutant sampling results and CO_2 monitoring results are presented. The analysis results which are gathered via future climate simulation results for the years of 2050 and 2080 are presented. The chapter concludes with a discussion of all analyses' results.

4.1. Monitoring Results

For this thesis' purpose, library's temperature and relative humidity parameters were monitored for two years between December 2019-November 2021. Compared T and RH measurements of outdoor which was monitored by O1 datalogger for December 2019-November 2020 and December 2020-November 2021 are given in Figure 4.1 and 4.2, respectively. Conversely T and RH measurements of outdoor for December 2019-November 2020 and December 2014-November 2015 are given in Figure 4.3 and 4.4, respectively.

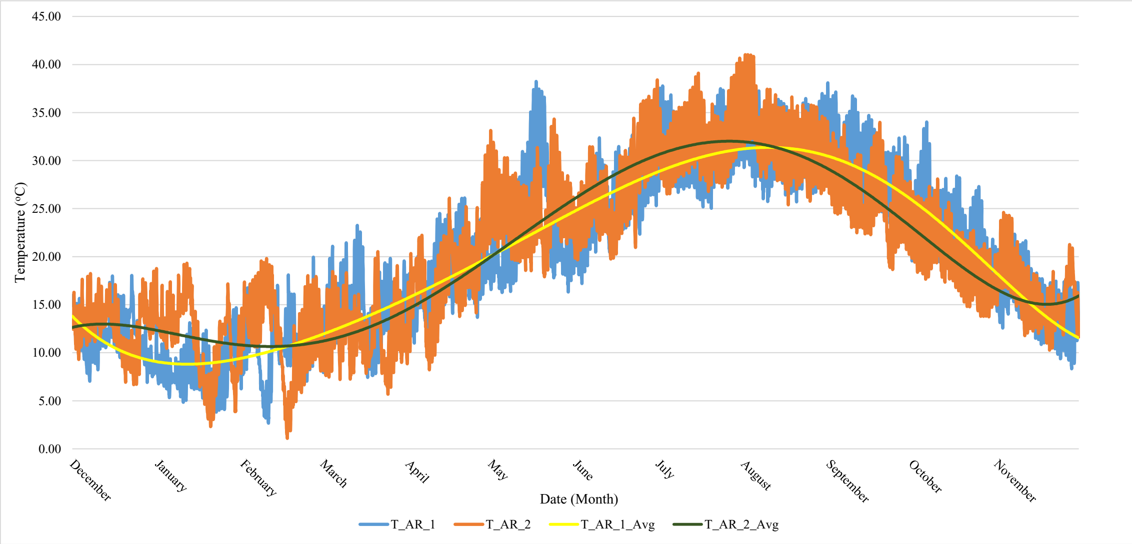


Figure 4.1. Temperature measurements of outdoor for 2019-2020 (T_AR_1) and 2020-2021 (T_AR_2)

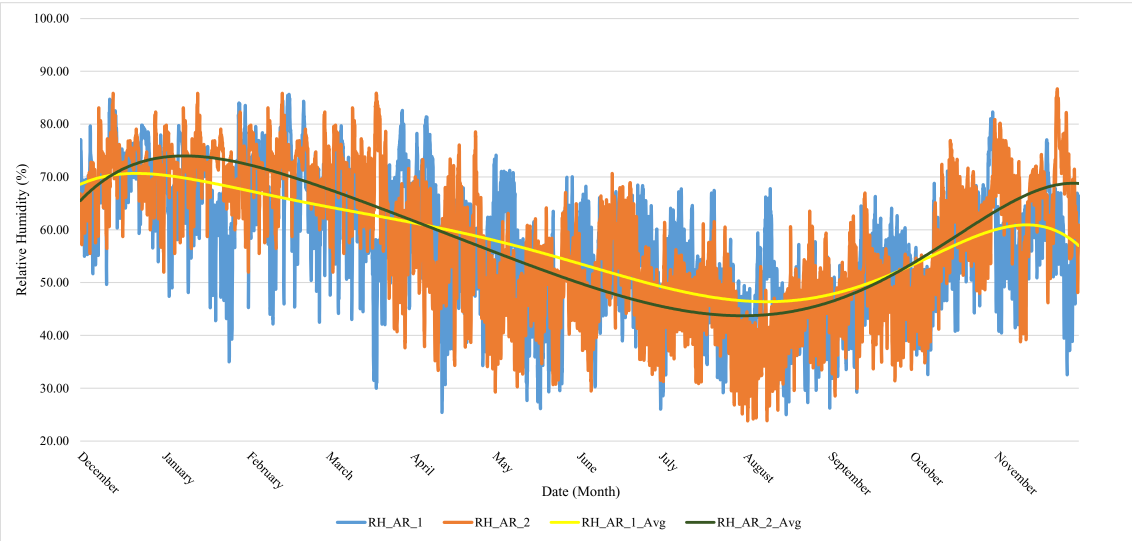


Figure 4.2. Relative humidity measurements of outdoor for 2019-2020 (RH_AR_1) and 2020-2021 (RH_AR_2)

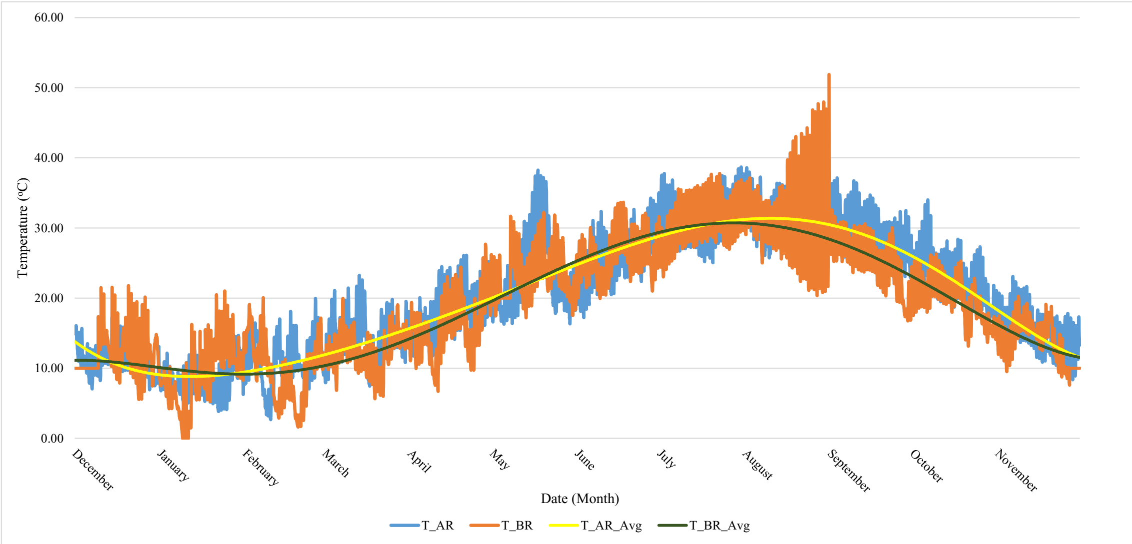


Figure 4.3. Temperature measurements of outdoor after (T_AR) and before restoration (T_BR)

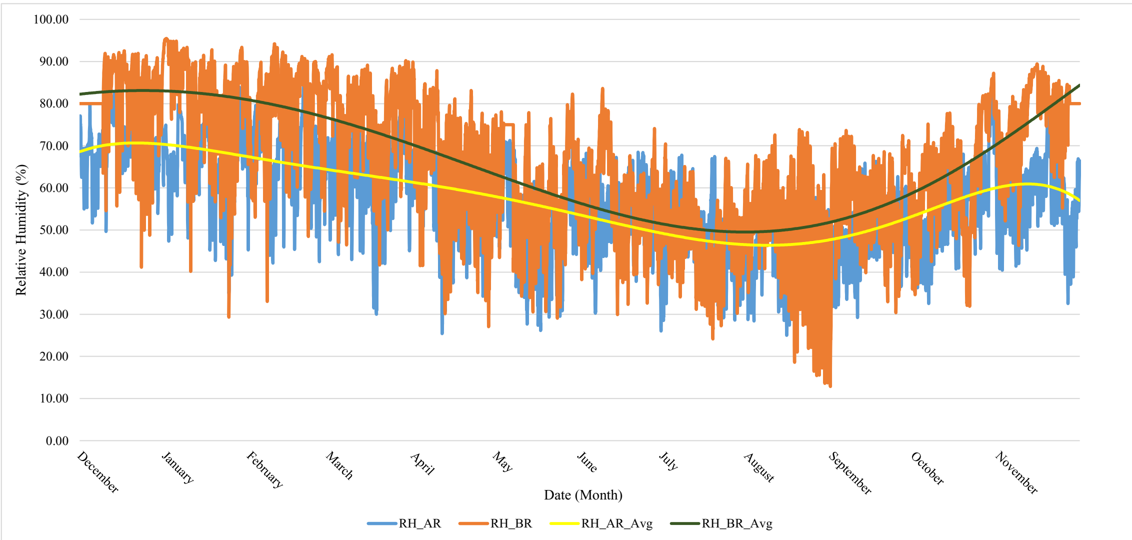


Figure 4.4. Relative humidity measurements of outdoor after (RH_AR) and before restoration (RH_BR)

The highest, lowest and average of outdoor's measured T and RH values in a monthly basis for the 2014-2015, 2019-2020 and 2020-2021 periods are given in Table 4.1. During 2014-2015 the highest measured T was 51.87°C, lowest T was -2.50°C and average was 19.03°C. the highest measured RH was 95.49%, lowest RH was 12.85% and average was 66.21%. Because of these extreme T and RH measurements, it may be interpreted that the outdoor datalogger was not sheltered as needed during August 2015. During 2019-2020 the highest measured T was 38.69°C, lowest T was 2.66°C and average was 19.86°C. The highest measured RH was 85.64%, lowest RH was 24.99% and average was 58.01%. Lastly, during 2020-2021 the highest measured T was 41.04°C, lowest T was 1.08°C and average was 20.08°C. The highest measured RH was 86.68%, lowest RH was 23.79% and average was 58.52%.

Table 4.1. Maximum, minimum and average of outdoor's T and RH values in a monthly basis for 2014-2015, 2019-2020 and 2020-2021

T (°C)	2014-2015			2019-2020			2020-2021		
	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
December	5.53	21.79	11.42	6.91	18.05	11.42	6.67	18.76	12.61
January	-2.50	21.03	8.75	3.81	14.68	8.02	2.31	19.33	11.14
February	1.61	20.05	9.50	2.66	19.96	10.82	1.08	19.81	11.54
March	5.64	19.95	12.31	7.43	23.25	13.89	5.68	20.53	11.54
April	6.70	27.70	16.16	11.00	26.11	17.57	8.22	30.59	17.38
May	17.19	32.21	23.59	16.26	38.24	23.20	17.90	34.33	24.50
June	19.94	33.67	26.24	17.21	35.03	25.73	19.66	37.41	26.51
July	23.02	37.77	31.14	25.04	38.69	30.94	26.52	40.66	31.66
August	20.32	51.87	29.94	25.70	38.60	30.96	25.40	41.04	31.89
September	16.73	32.59	25.36	22.53	37.15	28.54	18.66	34.09	26.05
October	13.15	26.28	19.80	16.25	34.02	22.40	13.74	28.09	19.53
November	7.59	20.26	13.67	8.33	23.08	14.48	10.26	24.60	15.94

RH (%)	2014-2015			2019-2020			2020-2021		
	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
December	41.15	94.31	82.72	49.63	84.75	71.22	51.97	85.84	70.75
January	29.29	95.49	81.83	34.98	84.02	66.07	51.97	85.84	71.81
February	33.03	94.22	78.64	42.14	85.64	68.12	55.49	85.84	72.10
March	41.68	91.62	76.68	29.99	82.60	63.96	37.64	85.87	67.39
April	27.05	88.14	63.61	25.41	81.39	58.34	33.36	78.56	57.03
May	29.04	82.26	58.71	26.13	74.14	52.59	29.27	67.06	49.28
June	29.92	83.61	56.40	26.03	68.49	54.60	29.47	70.68	51.66
July	24.14	70.47	47.46	28.54	67.77	48.95	25.11	61.56	46.02
August	12.85	73.86	51.11	24.99	67.80	45.37	23.79	63.53	42.82
September	30.39	73.65	56.58	29.22	66.32	50.67	28.53	66.96	48.22
October	31.87	87.24	63.67	32.55	82.32	57.52	33.54	77.02	58.32
November	46.31	89.44	77.54	32.55	77.04	59.11	38.78	86.68	67.79

Manuscript zone was monitored by M1 datalogger and the compared T and RH measurements of manuscript zone for December 2019-November 2020 and December 2020-November 2021 are given in Figure 4.5 and 4.6, respectively. Figure 4.5 shows several significant fluctuations of temperature for 1-2 day long periods and correspond to times which HVAC system either stopped working or was under maintenance and turned off. According to library manager, the HVAC system stops working during summer due to high temperatures increasing the internal pressure of exterior unit of the system which is directly exposed to sunlight.

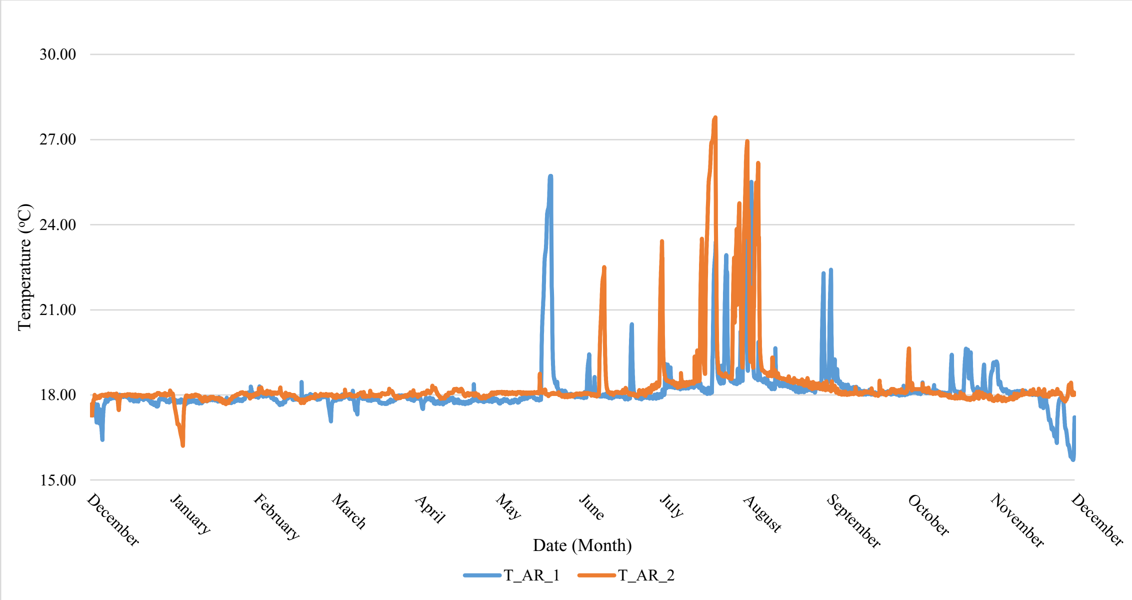


Figure 4.5. Temperature measurements of manuscript zone for 2019-2020 (T_AR_1) and 2020-2021 (T_AR_2)

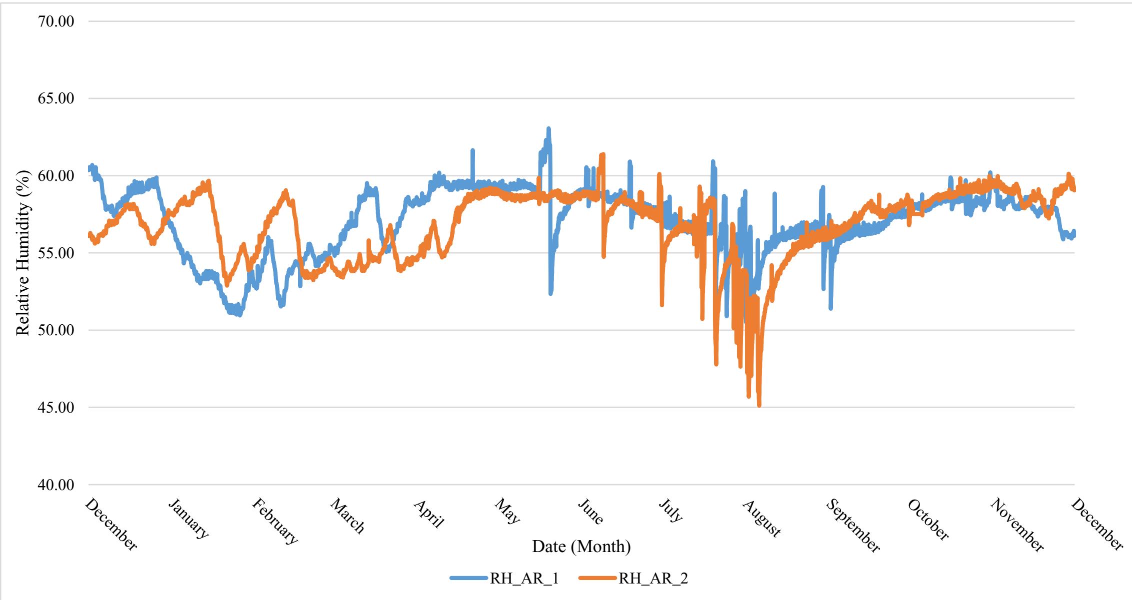


Figure 4.6. Relative humidity measurements of manuscript zone for 2019-2020 (RH_AR_1) and 2020-2021 (RH_AR_2)

The compared T and RH measurements of manuscript zone for December 2019-November 2020 and December 2014-November 2015 are given in respectively Figure 4.7 and 4.8 which show far higher T and RH fluctuations during the pre-restoration period.

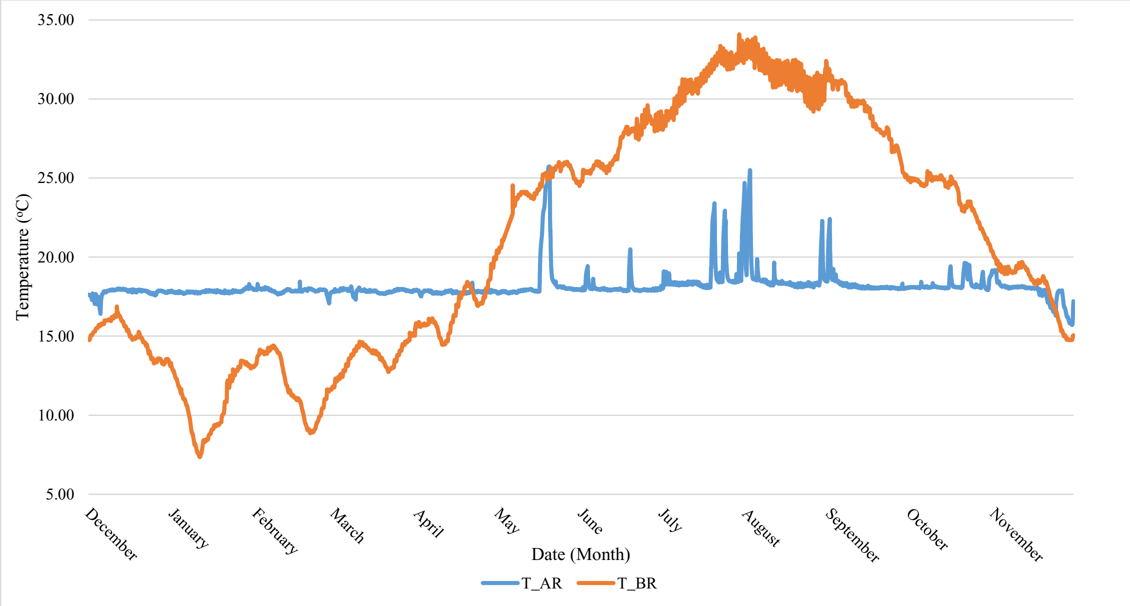


Figure 4.7. Temperature measurements of manuscript zone after (T_AR) and before restoration (T_BR)

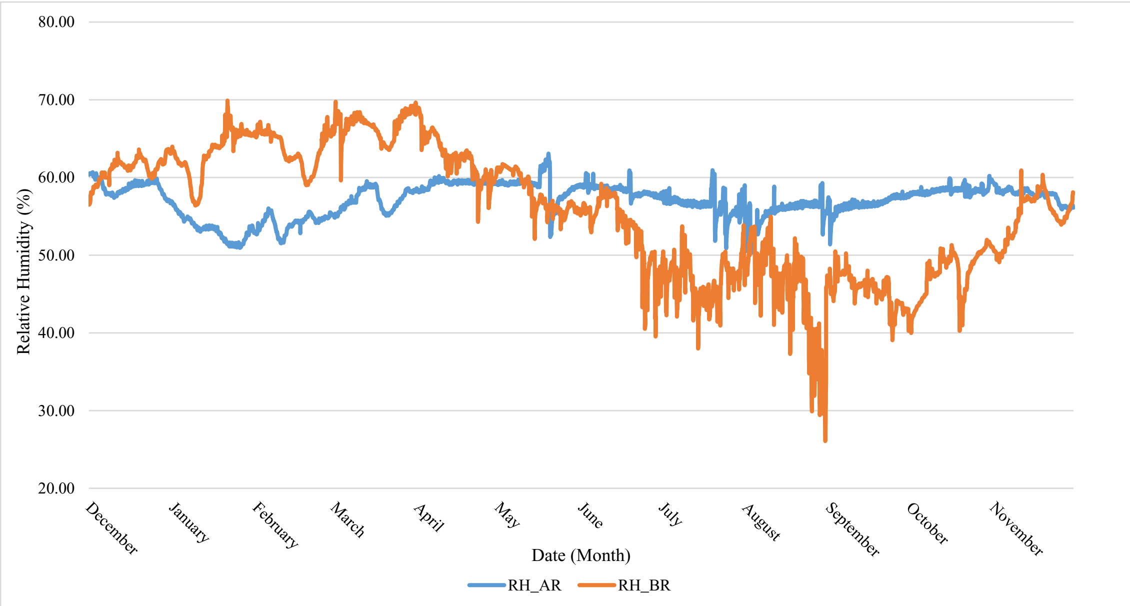


Figure 4.8. Relative humidity measurements of manuscript zone after (RH_AR) and before restoration (RH_BR)

The highest, lowest and average of manuscript zone's measured T and RH values in a monthly basis for 2014-2015, 2019-2020 and 2020-2021 periods are given in Table 4.2. Among all periods, the 2014-2015 period contains both the lowest and highest recorded T and RH values due to the free-floating hygrothermal behavior of the library during that period. During 2014-2015 the highest measured T was 34.09°C, lowest T was

7.36°C and average was 21.10°C. The highest measured RH was 69.91%, lowest RH was 26.10% and average was 55.74%. During 2019-2020 the highest measured T was 25.72°C, lowest T was 15.71°C and average was 18.15°C. The highest measured RH was 63.07%, lowest RH was 50.27% and average was 57.06%. Finally, during 2020-2021 the highest measured T was 27.79°C, lowest T was 16.21°C and average was 18.34°C. The highest measured RH was 61.40%, lowest RH was 45.11% and average was 56.79%.

Table 4.2. Maximum, minimum and average of manuscript zone's T and RH values in a monthly basis for 2014-2015, 2019-2020 and 2020-2021

T (°C)	2014-2015			2019-2020			2020-2021		
	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
December	13.06	16.88	14.90	16.42	18.01	17.76	17.27	18.16	17.96
January	7.36	13.45	10.81	17.67	18.30	17.83	16.21	18.09	17.80
February	8.86	14.41	11.79	17.07	18.45	17.87	17.71	18.26	17.99
March	11.76	15.82	13.76	17.31	18.15	17.85	17.88	18.22	17.99
April	14.45	20.43	16.79	17.51	18.38	17.79	17.87	18.33	18.04
May	20.25	26.03	24.18	17.70	25.72	18.65	17.92	18.75	18.05
June	24.77	29.61	27.07	17.84	20.50	18.05	17.94	22.51	18.34
July	28.05	34.09	31.25	17.99	24.69	18.90	18.26	27.79	20.25
August	29.20	33.90	31.60	18.08	25.51	18.78	18.16	26.94	19.43
September	24.88	31.91	28.79	17.97	22.41	18.24	17.97	18.91	18.10
October	20.31	25.44	23.79	17.91	19.63	18.28	17.82	19.64	18.05
November	14.75	20.29	18.06	15.71	19.18	17.70	17.77	18.43	17.98

RH (%)	2014-2015			2019-2020			2020-2021		
	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
December	56.50	63.65	61.17	56.68	60.69	58.75	55.59	58.19	56.85
January	56.39	69.91	63.15	50.95	56.79	53.28	52.88	59.68	56.61
February	59.01	67.80	63.63	51.52	56.03	54.21	53.23	59.05	55.84
March	59.63	69.77	66.65	54.82	59.53	57.15	53.41	56.80	54.48
April	54.30	68.99	62.62	58.09	61.66	59.26	54.52	59.21	57.04
May	52.09	61.72	57.88	52.34	63.07	58.85	58.15	59.86	58.68
June	39.54	59.20	53.42	56.64	60.92	58.40	54.74	61.40	58.26
July	37.99	53.87	46.88	50.88	60.94	56.47	47.64	59.68	55.35
August	26.10	54.97	45.69	50.27	59.28	55.59	45.11	56.97	53.60
September	39.07	50.49	45.49	51.39	58.21	56.57	55.85	58.78	57.37
October	39.99	51.99	47.61	57.43	60.21	58.38	56.78	60.00	58.64
November	49.10	60.92	54.96	55.88	59.43	57.74	57.22	60.13	58.78

Lastly, comparison of T and RH values monitored by manuscript zone's (M1), west of library area's (H2) and east of library area's (H1) dataloggers during December 2019-November 2020 are given in Figure 4.9 and 4.10. The highest and lowest measured values, average of measured values and difference between the averages of H1 and H2's values to M1's values in a monthly basis are given in Table 4.3. When investigated, T and RH measurements for all three dataloggers show very similar results which indicates the success of HVAC system's uniform climatization of entire main hall. For all months

M1’s measured T values were higher than H1 and H2’s values and M1’s measured RH values were lower than H1 and H2’s values which shows the impact of manuscript cage.

Table 4.3. Maximum, minimum and average of library area’s dataloggers’ T and RH values in a monthly basis for 2019-2020

T (°C)	Manuscript Zone			Library Area (West)				Library Area (East)			
	Min	Max	Avg	Min	Max	Avg	Diff_Avg	Min	Max	Avg	Diff_Avg
December	16.42	18.01	17.76	15.75	17.65	17.39	-0.37	15.94	17.99	17.66	-0.10
January	17.67	18.30	17.83	17.36	17.68	17.49	-0.34	17.80	18.08	17.92	0.09
February	17.07	18.45	17.87	16.61	17.75	17.50	-0.37	16.78	18.39	17.82	-0.05
March	17.31	18.15	17.85	16.94	17.70	17.52	-0.33	17.05	17.91	17.66	-0.19
April	17.51	18.38	17.79	17.23	18.52	17.58	-0.21	17.34	18.28	17.57	-0.22
May	17.70	25.72	18.65	17.48	25.78	18.48	-0.17	17.36	25.70	18.31	-0.34
June	17.84	20.50	18.05	17.59	20.57	17.94	-0.11	17.39	20.36	17.65	-0.41
July	17.99	24.69	18.90	17.93	24.67	18.79	-0.11	17.55	24.53	18.46	-0.44
August	18.08	25.51	18.78	17.93	25.56	18.58	-0.20	17.56	25.45	18.26	-0.51
September	17.97	22.41	18.24	17.68	22.35	18.00	-0.24	17.38	22.33	17.74	-0.49
October	17.91	19.63	18.28	17.54	19.44	17.97	-0.31	17.44	19.50	17.84	-0.44
November	15.71	19.18	17.70	15.29	18.89	17.22	-0.48	15.41	19.03	17.43	-0.27

RH (%)	Manuscript Zone			Library Area (West)				Library Area (East)			
	Min	Max	Avg	Min	Max	Avg	Diff_Avg	Min	Max	Avg	Diff_Avg
December	56.68	60.69	58.75	58.06	63.15	60.47	1.72	56.67	62.45	59.41	0.66
January	50.95	56.79	53.28	52.62	58.34	54.95	1.67	51.08	57.01	53.49	0.22
February	51.52	56.03	54.21	52.76	59.09	56.31	2.10	51.27	58.04	55.06	0.85
March	54.82	59.53	57.15	55.84	62.40	59.10	1.95	54.73	61.73	58.27	1.12
April	58.09	61.66	59.26	59.79	62.46	60.77	1.51	59.09	62.08	60.33	1.07
May	52.34	63.07	58.85	53.16	63.72	60.56	1.71	51.90	63.87	60.66	1.80
June	56.64	60.92	58.40	58.42	62.04	60.45	2.06	58.25	62.94	61.07	2.67
July	50.88	60.94	56.47	52.71	61.75	58.71	2.25	51.55	62.66	59.56	3.09
August	50.27	59.28	55.59	52.37	60.58	58.54	2.95	51.33	61.86	59.35	3.76
September	51.39	58.21	56.57	53.30	60.91	59.71	3.13	52.96	61.79	60.45	3.88
October	57.43	60.21	58.38	59.22	61.51	60.62	2.24	59.22	62.07	60.97	2.58
November	55.88	59.43	57.74	57.15	61.28	59.66	1.92	56.19	61.04	58.91	1.17

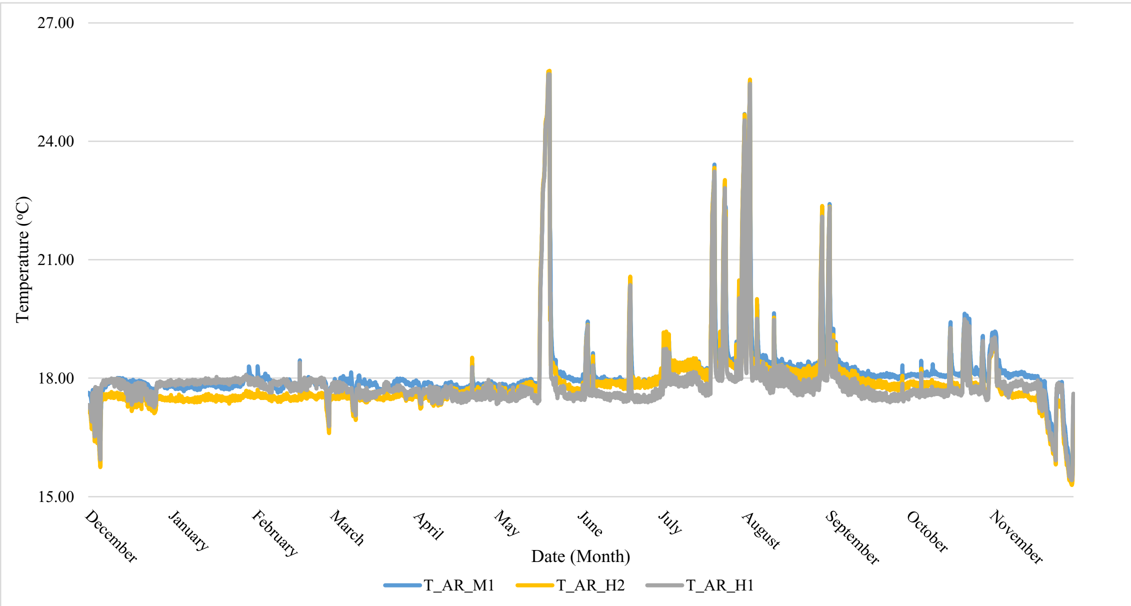


Figure 4.9. Temperature measurements of main hall for 2019-2020

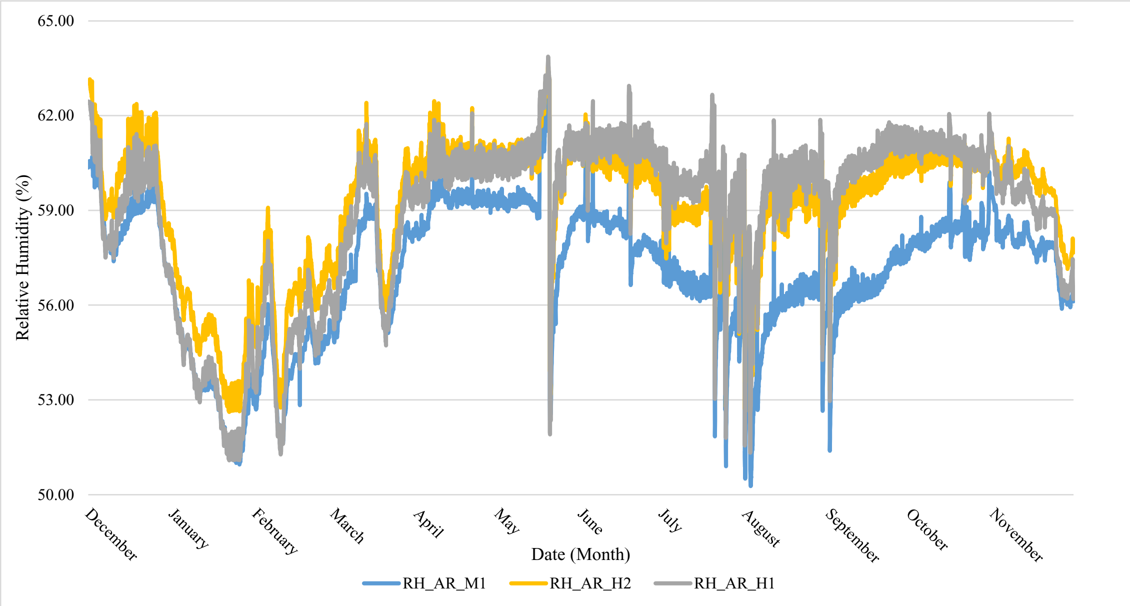


Figure 4.10. Relative humidity measurements of main hall for 2019-2020

4.1.1. General Climate Risk Assessment

As previously mentioned Tire Necip Paşa Library's indoor climate is investigated according to AA, A1 and A2 climate control classes of ASHRAE Chapter 23. Other climate control classes were not considered since they do not provide necessary preservation conditions for the longevity of library's manuscripts (ASHRAE, 2011). For this assessment, a year-long monitored data of the manuscript zone's datalogger is used which is between December 2019-November 2020. The general climate risk assessment results of the library based on allowed short fluctuations and seasonal adjustments of these control classes are shown in Figure 4.11-4.16.

The results for climate class of AA which provides the best preservation conditions for highly vulnerable cultural objects are given in Figure 4.11 and 4.12. The results for this class show that after the restoration process and HVAC system integration, library's T and RH were within the bandwidths by 97%. Overall result was 94% which is datapoints that both T and RH measurement are within their respective bandwidths (Figure 4.11). Conversely, pre-restoration T and RH data resulted in the bandwidths of 46% and 30% respectively for T and RH which results in a 20% overall result (Figure 4.12).

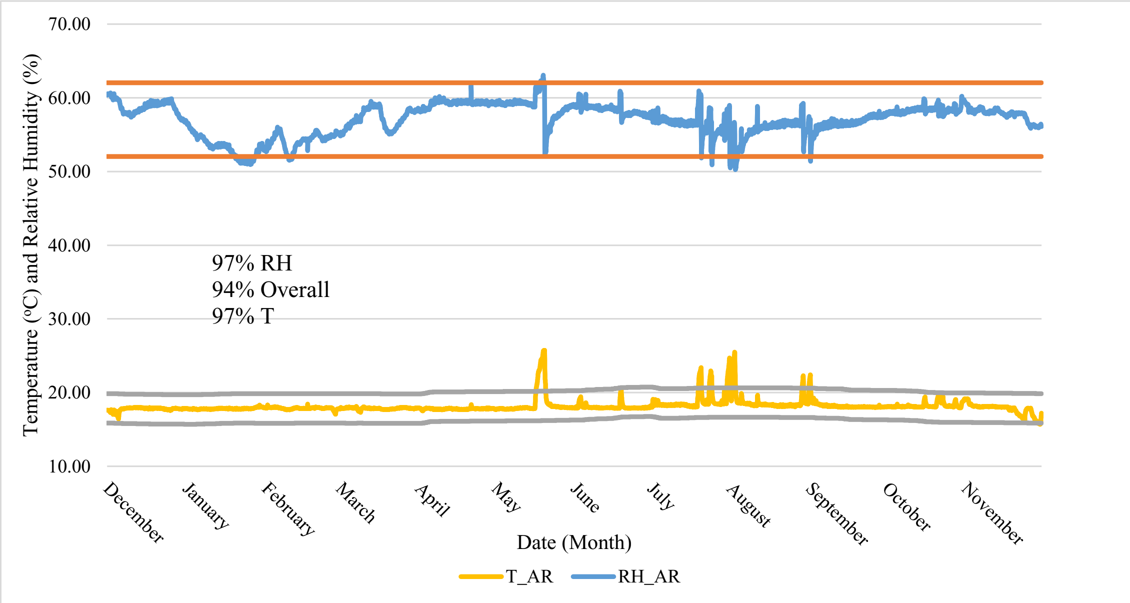


Figure 4.11. Temperature and relative humidity measurements after restoration with AA control class bandwidths

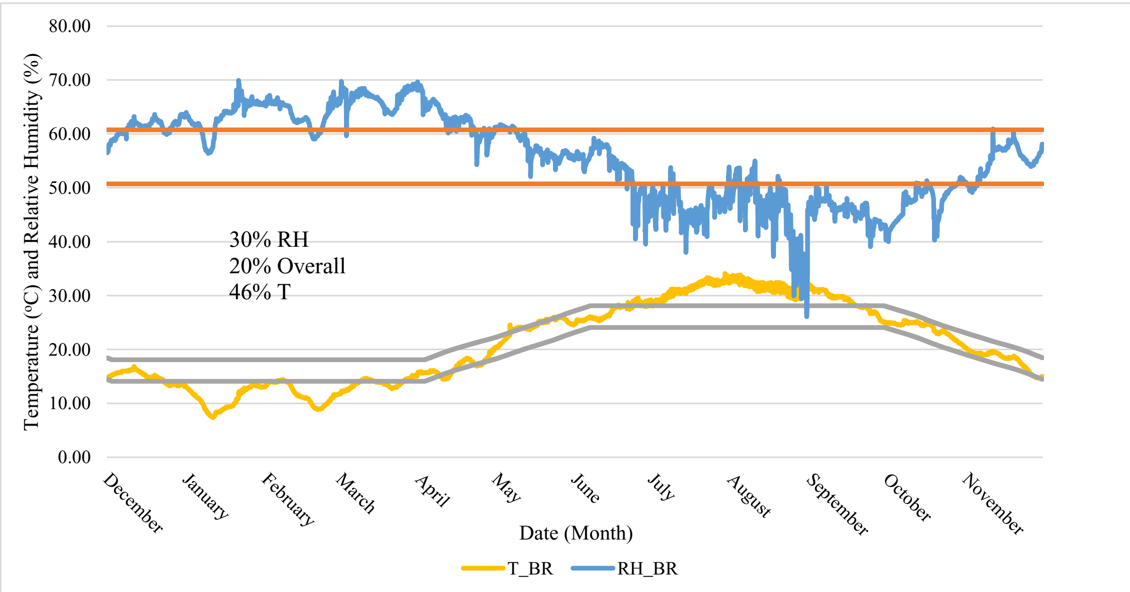


Figure 4.12. Temperature and relative humidity measurements before restoration with AA control class bandwidths

The post-restoration T and RH data for climate control class of A1 are given in Figure 4.13 and show similar results with being within the bandwidths of 97% and 99% respectively which corresponds to 97% overall result. When compared to AA results, pre-restoration T and RH data show far better results for A1 with being within the bandwidths of 62% and 92% respectively which results in a 60% overall result (Figure 4.14).

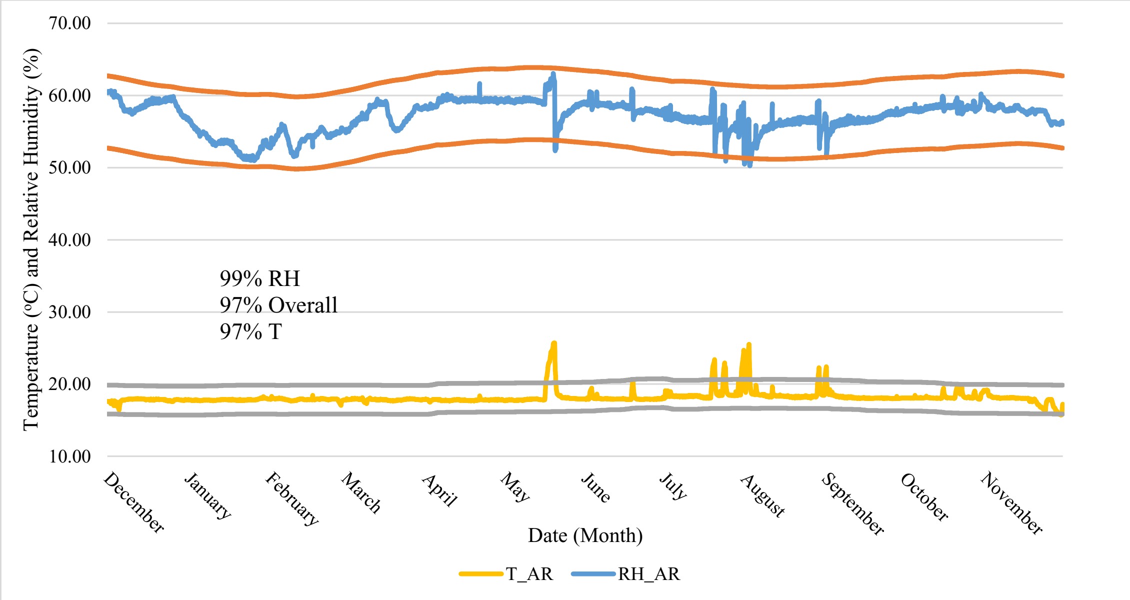


Figure 4.13. Temperature and relative humidity measurements after restoration with A1 control class bandwidths

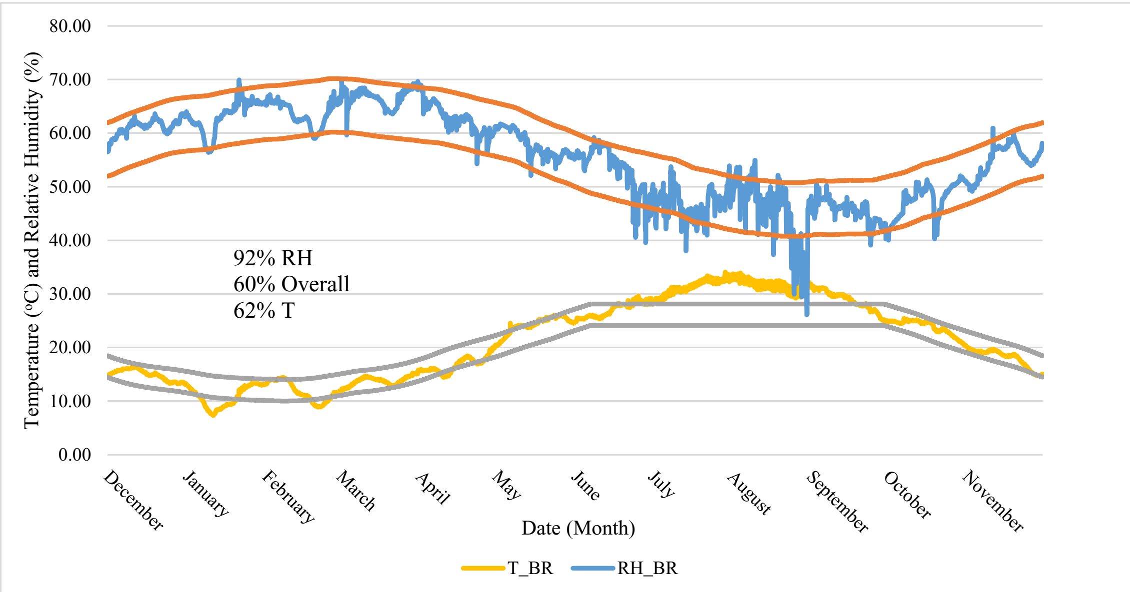


Figure 4.14. Temperature and relative humidity measurements before restoration with A1 control class bandwidths

Lastly post-restoration T and RH data for climate control class of A2 are given in Figure 4.15 and show similar results to results of A1 with being within the bandwidths of 97% and 100% respectively which results in a 97% overall result. And pre-restoration monitored T and RH data show worse results than A1 climate control class results with being in the bandwidths of 62% and 77% respectively which results in a 47% overall result (Figure 4.16).

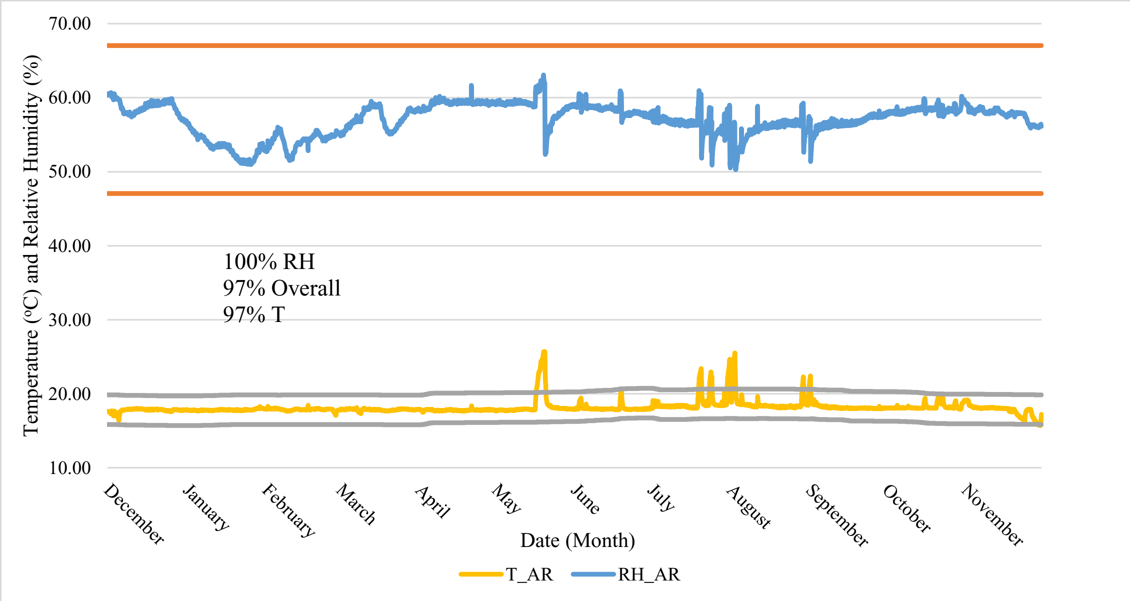


Figure 4.15. Temperature and relative humidity measurements after restoration with A2 control class bandwidths

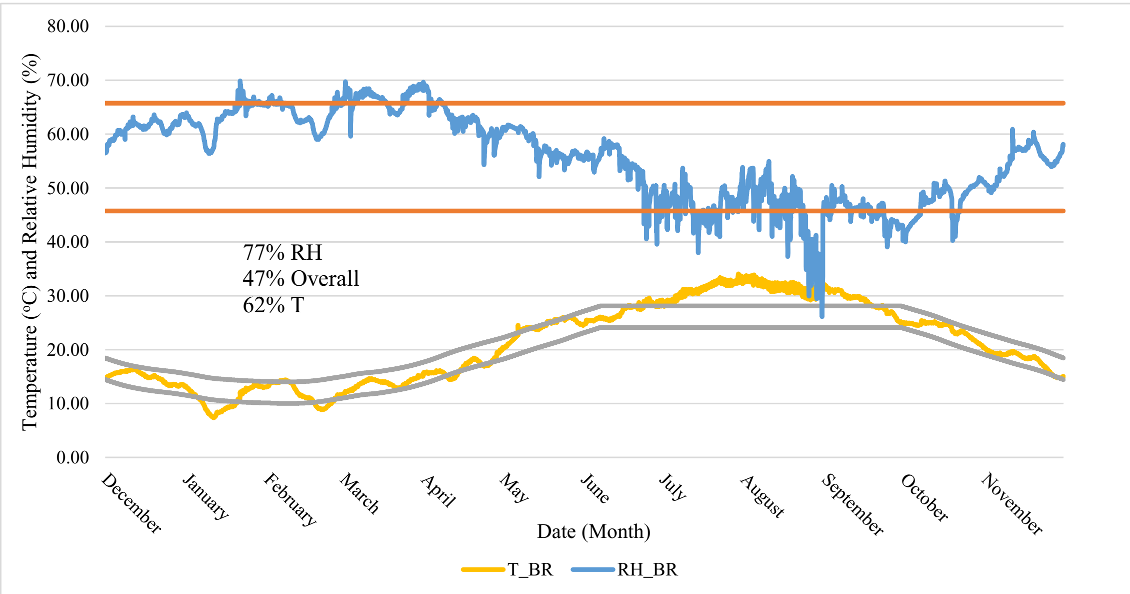


Figure 4.16. Temperature and relative humidity measurements before restoration with A2 control class bandwidths

When results are investigated in a monthy basis according to Table 4.4, the post-restoration monitored data generally shows good results for the climate control class of

AA. The month with lowest bandwidth for T was found out to be May with a result of 87%, while the month with lowest RH and overall bandwidth was January with 75%. The season with lowest bandwidth was winter with 90%. In the case of climate control class of A1, the month with worst T result was May with 88%, the month with worst RH result was August with 98% and the month with worst overall result was May with 87%. Lastly, in the case of climate control class of A2, the month with worst T and overall result was May with 87%, but all months were within the RH bandwith with 100%.

Conversely, the monitored data of pre-restoration show worse results for all climate control classes which does not satisfy the preservation requirements. For the climate control class of AA, the month with highest T bandwidth was found out to be October with 100%, while January and August were not within the bandwidth at all. The month with highest bandwith for RH was November with 86%. The month with highest overall bandwidth was again November with 80%.

The climate control class of A1 showed the best pre-restoration results among all classes. The T results of all months except August were somewhat in the bandwidth with the highest T bandwidth results being 100% for the months of December, March and October. For RH and overall results, December was the best month with a result of 100%.

Table 4.4. Pre- and post-restoration temperature and relative humidity results according to climate classes' bandwidths on a monthly basis (cont. on next page)

%	AA					
	T_AR	T_BR	RH_AR	RH_BR	Ov_AR	Ov_BR
December	100.00	71.64	100.00	33.06	100.00	25.27
January	100.00	0.00	74.73	17.34	74.73	0.00
February	100.00	11.64	94.25	14.80	94.25	0.00
Winter	100.00	28.11	89.56	21.89	89.56	8.61
March	100.00	35.62	100.00	0.27	100.00	0.00
April	100.00	70.97	100.00	28.06	100.00	15.83
May	87.50	66.67	97.45	75.94	87.50	47.18
Spring	95.79	57.61	99.14	34.83	95.79	21.06
June	100.00	67.92	100.00	75.00	100.00	66.39
July	88.84	0.27	98.92	3.49	88.31	0.00
August	92.74	0.00	95.97	15.19	89.78	0.00
Summer	93.80	22.24	98.28	30.75	92.62	21.65
September	98.19	37.64	99.58	0.00	97.92	0.00
October	100.00	100.00	100.00	12.50	100.00	12.5
November	95.83	94.44	100.00	85.56	95.83	80.00
Autumn	98.03	77.61	99.86	32.46	97.94	30.63
Overall	96.89	46.36	96.72	30.00	93.98	20.49

Table 4.4 (cont.)

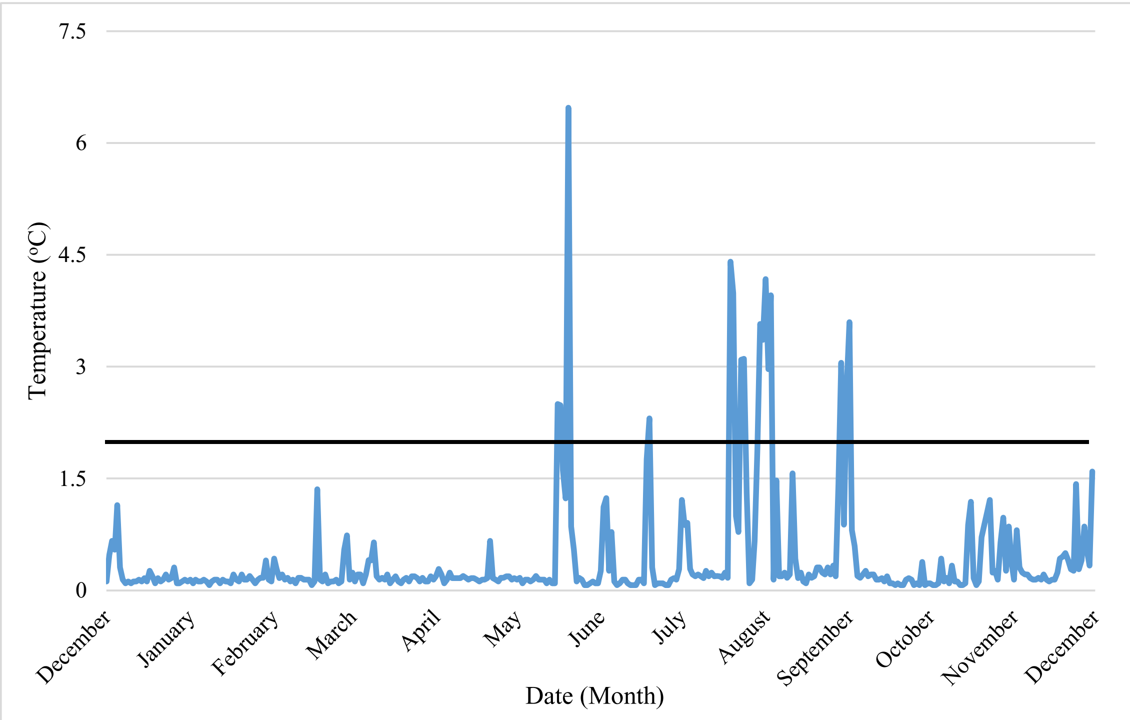
%	A1					
	T_AR	T_BR	RH_AR	RH_BR	Ov_AR	Ov_BR
December	100.00	100.00	100.00	100.00	100.00	100.00
January	100.00	50.27	100.00	91.80	100.00	49.06
February	100.00	59.05	100.00	92.10	100.00	59.05
Winter	100.00	70.01	100.00	94.69	100.00	69.60
March	100.00	100.00	100.00	93.95	100.00	93.95
April	100.00	70.97	100.00	96.94	100.00	68.89
May	87.50	66.67	98.39	99.87	86.69	66.53
Spring	95.79	79.30	99.46	96.92	95.52	76.54
June	100.00	67.92	100.00	91.94	100.00	66.53
July	88.84	0.27	99.60	86.02	88.71	0.27
August	92.74	0.00	97.58	66.67	91.40	0.00
Summer	93.80	22.24	99.05	81.43	93.30	21.78
September	98.19	37.64	99.86	96.94	98.19	34.58
October	100.00	100.00	100.00	91.80	100.00	91.80
November	95.83	94.44	100.00	99.58	95.83	94.03
Autumn	98.03	77.61	99.95	96.06	98.03	73.67
Overall	96.89	62.23	99.61	92.26	96.70	60.34

%	A2					
	T_AR	T_BR	RH_AR	RH_BR	Ov_AR	Ov_BR
December	100.00	100.00	100.00	100.00	100.00	100.00
January	100.00	50.27	100.00	84.68	100.00	34.95
February	100.00	59.05	100.00	81.61	100.00	45.98
Winter	100.00	70.01	100.00	88.92	100.00	60.62
March	100.00	100.00	100.00	25.67	100.00	25.67
April	100.00	70.97	100.00	85.97	100.00	56.94
May	87.50	66.67	100.00	100.00	87.50	66.67
Spring	95.79	79.30	100.00	70.38	95.79	49.68
June	100.00	67.92	100.00	94.58	100.00	67.64
July	88.84	0.27	100.00	65.46	88.84	0.27
August	92.74	0.00	100.00	63.17	92.74	0.00
Summer	93.80	22.24	100.00	74.18	93.80	22.15
September	98.19	37.64	100.00	53.61	98.19	3.06
October	100.00	100.00	100.00	69.89	100.00	69.89
November	95.83	94.44	100.00	100.00	95.83	94.44
Autumn	98.03	77.61	100.00	74.45	98.03	55.95
Overall	96.89	62.23	100.00	76.96	96.89	47.04

Lastly, the individual monthly results of pre-restoration for A2 climate control class were somewhat better than A1 climate control class results, but the overall results were worse. The months with highest T bandwidth results were December, March and October with 100%. For RH December, May and November were the best months with a result of 100%. The month with highest overall bandwidth was December with 100%.

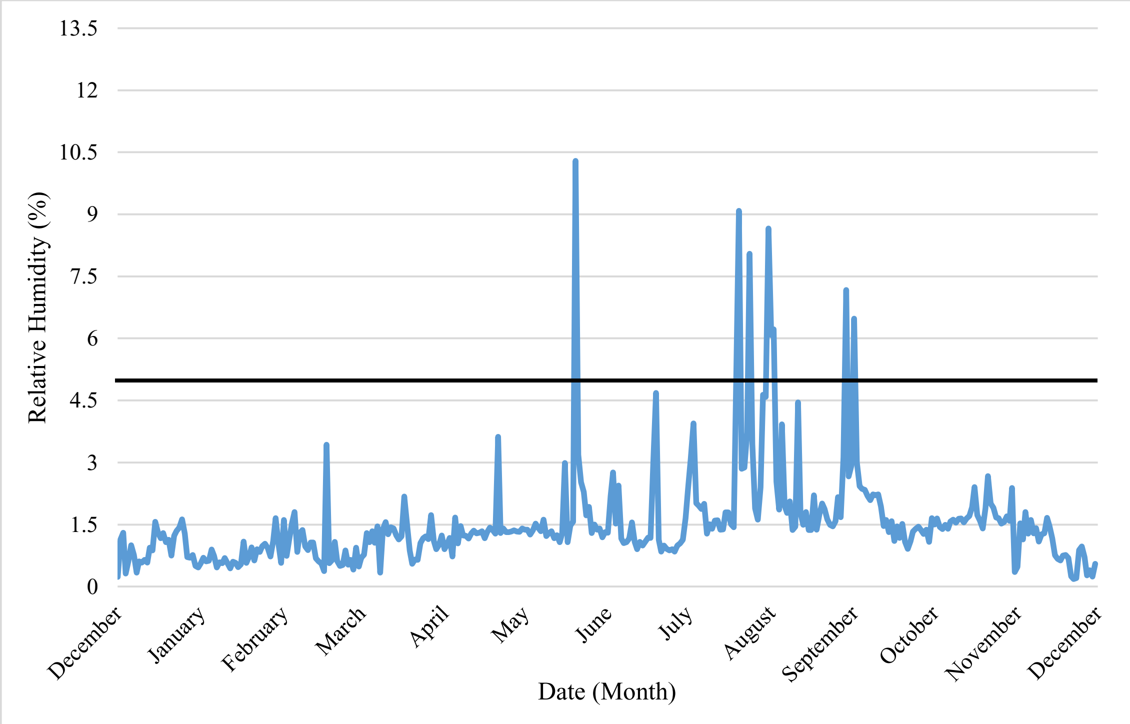
4.1.2. Mechanical Degradation Risk Assessment

To assess the risk of mechanical degradation, the short fluctuations should be separately analyzed according to the short fluctuation limits of ASHRAE Chapter 23's climate control classes (Table 3.2) Figure 4.17 shows the maximum daily T and RH differences which were monitored post-restoration. When investigated, most of the monitored daily T and RH fluctuations were below the ±2 K and ±5% limits respectively which satisfy the requirements of all control classes. Figure 4.18 shows the cumulative frequencies of maximum daily T and RH differences, respectively. According to the cumulative frequency calculations, 95.64% of the post-restoration T differences were below ±2 K limit, while 97.82% of the RH differences were below ±5% RH limit.



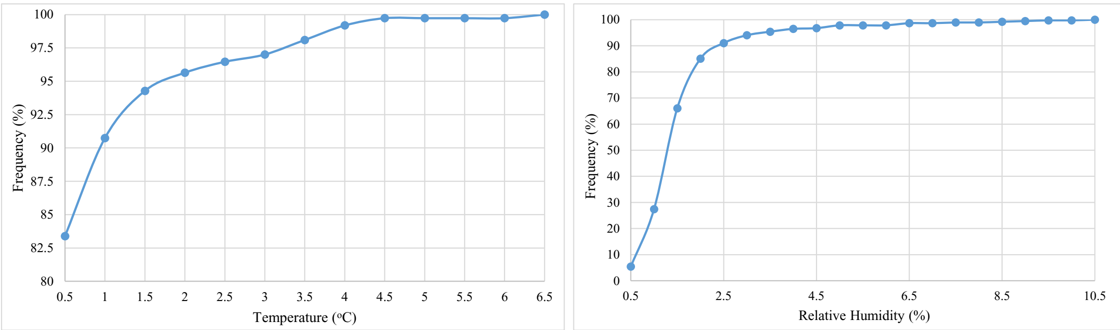
(a)

Figure 4.17. Maximum daily T (a) and RH (b) differences after restoration (cont. on next page)



(b)

Figure 4.17 (cont.)

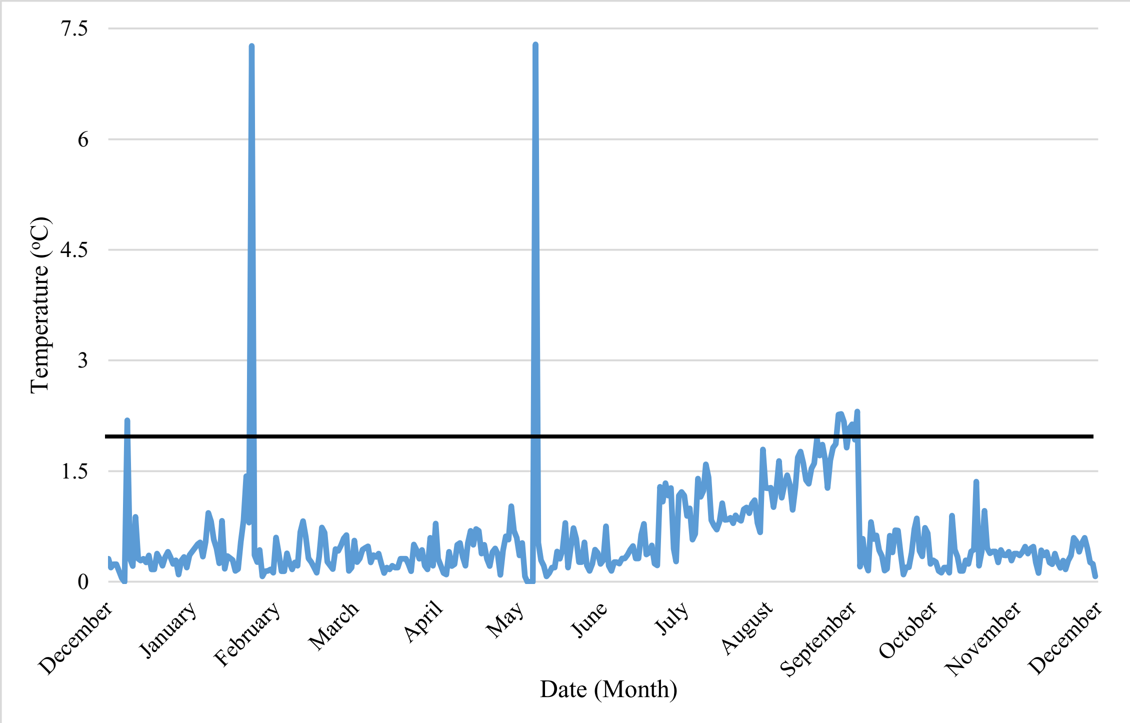


(a) (b)

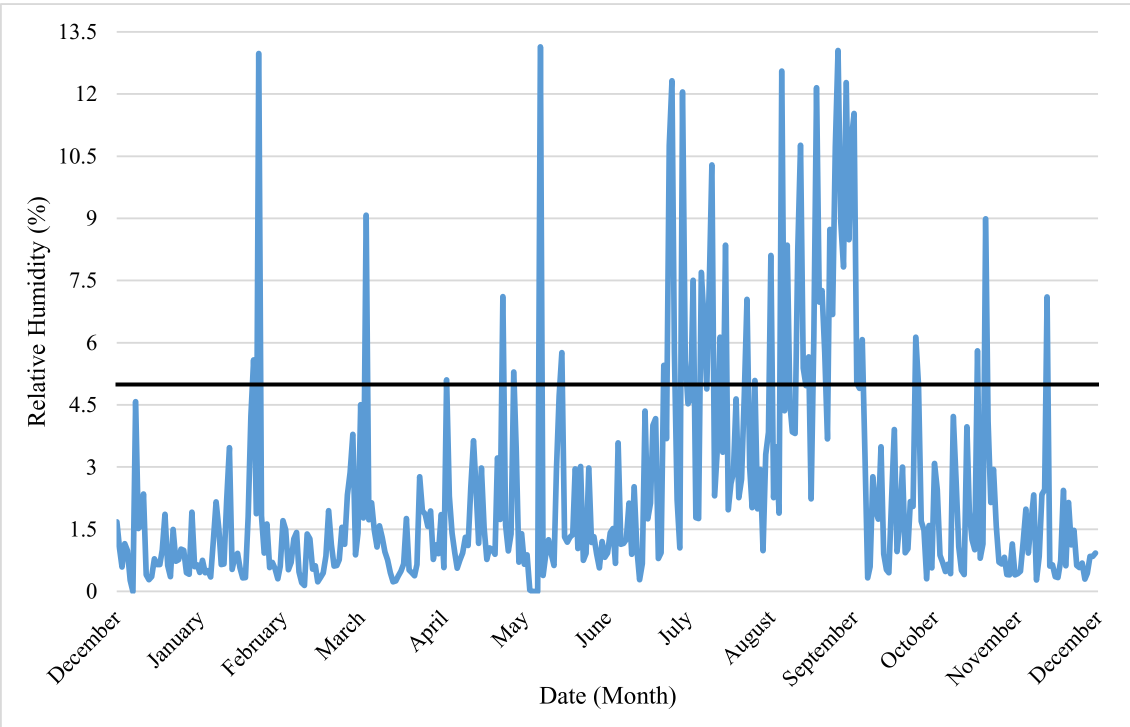
Figure 4.18. Cumulative frequencies of T (a) and RH (b) differences after restoration

Conversely Figure 4.19 shows the maximum hourly T and RH differences which were monitored pre-restoration. While most of the monitored hourly T fluctuations were below the ±2 K limit, a considerable amount of RH fluctuations were over ±5% limit. It can be said that T fluctuations of pre-restoration satisfied the requirements of all control classes in terms of mechanical degradation, while RH results are worse. Figure 4.20 shows the cumulative frequencies of respectively maximum daily T and RH differences. According to cumulative frequency calculations 97.54% of the pre-restoration T differences were below ±2 K limit which is similar to post-restoration results, while

86.1% of the RH differences were below ±5% RH limit which is worse than post-restoration results.

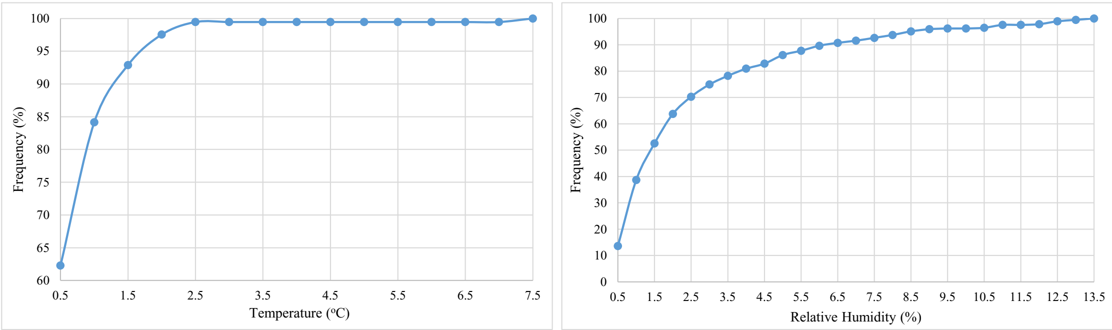


(a)



(b)

Figure 4.19. Maximum daily T (a) and RH (b) differences before restoration



(a) (b)

Figure 4.20. Cumulative frequencies of T (a) and RH (b) differences before restoration

4.1.3. Chemical Degradation Risk Assessment

The results of the chemical degradation risk assessment of manuscript zone based on the pre- and post-restoration monitored T and RH data in terms of LM can be found in Figure 4.21. According to the post-restoration data, the manuscripts were under low risk of chemical degradation with a calculated eLM value of 1.08 except short time periods which HVAC system was under maintenance. The lowest calculated LM value was 0.34 in May, while the highest was 1.56 in November. The pre-restoration data showed that manuscripts were under high risk of chemical degradation with a calculated eLM value of 0.54. The lowest calculated LM value was 0.15 in July, while the highest was 5.30 in January. The most risky period was between the months of May and October, while January and February were the months with lowest risk of chemical degradation.

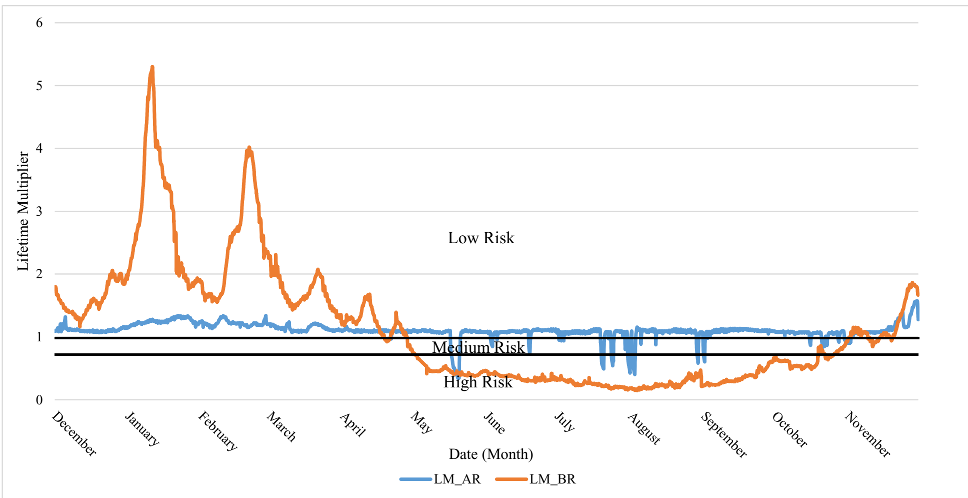


Figure 4.21. LM values of the manuscript zone for pre-restoration (LM_BR) and post-restoration (LM_AR)

4.1.4. Biological Degradation Risk Assessment

The biological degredation risk assessment of manuscript zone for pre- and post-restoration periods were done with the use of isopleths and superimposing the measured indoor T and RH data during these periods to the limit curves. The results of this assessment can be seen in Figure 4.22 and 4.23. At these figures, the blue limit curve is created via Equation 3.3 and is for porous materials, while the green limit curve is created via Equation 3.4 and is for wooden materials.

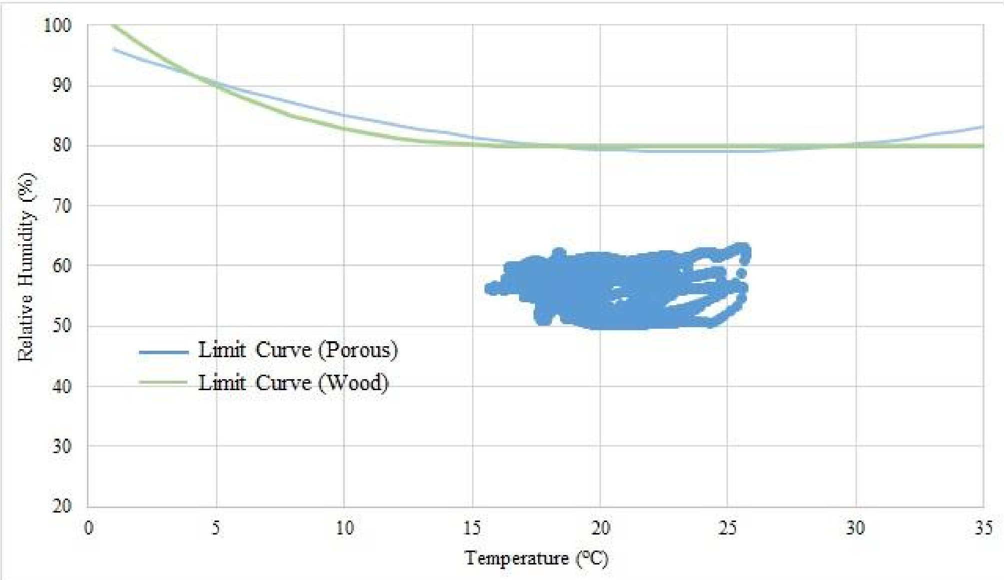


Figure 4.22. Mould growth risk of the manuscript zone after restoration

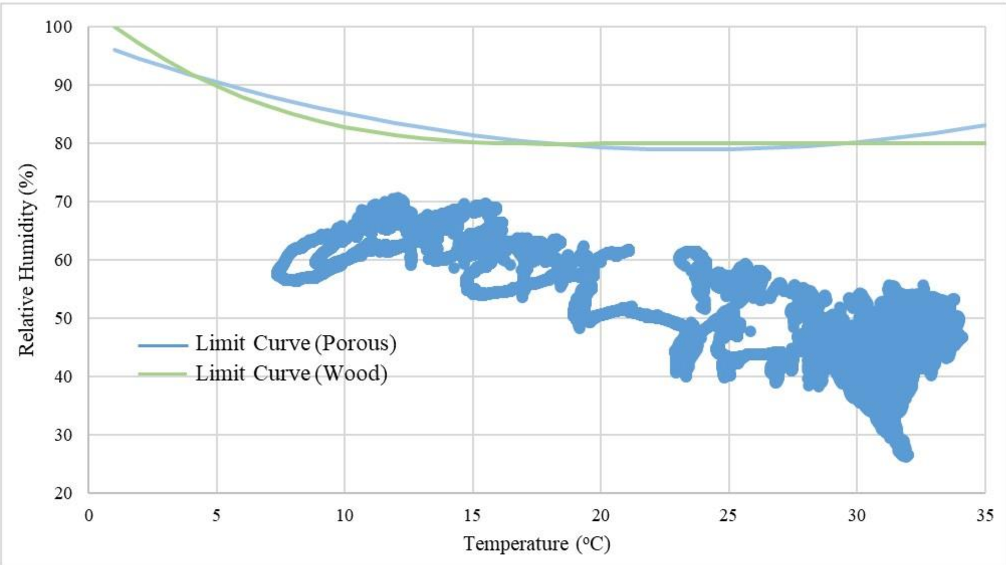
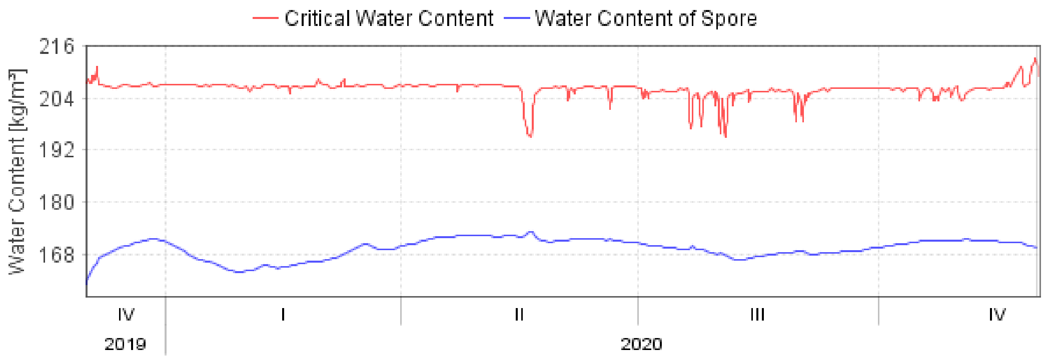


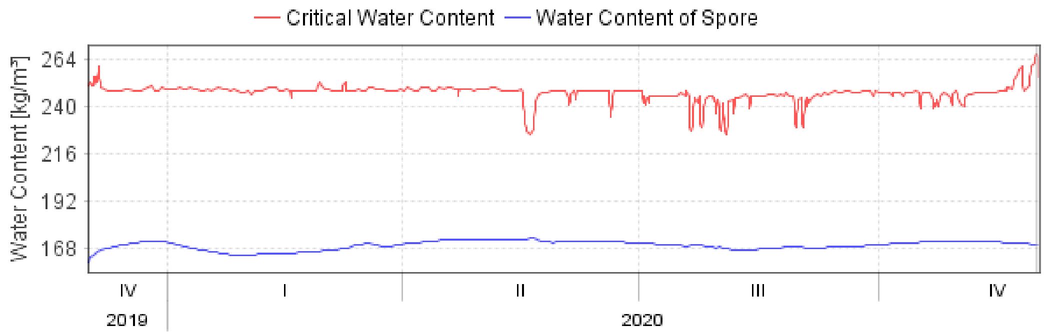
Figure 4.23. Mould growth risk of the manuscript zone before restoration

Figure 4.22 and 4.23 show that manuscript zone was under no risk of biological degradation during both pre- and post-restoration periods with a MRF result of 0.00. While the temperature measurements of post-restoration are within used equations' limits, some temperature measurements of pre-restoration are above the Equation 3.3's 30°C limit. But at these measurement points, the measured RH values are well below the limit curve which makes the final results acceptable. During post-restoration, the maximum measured RH was 63.07%, while during pre-restoration the maximum measured RH was 69.91% which pose no risk of biological degradation.

The measured data of both periods were also analyzed in WUFI-Bio according to Sedlbauer's substrate classes of I and II. The substrate class I is used for substrates such as wall paper, plaster boards and bio-degradable building materials, while the substrate class II is used for less bio-utilizable substrates like plasters, mineral based materials and wood products. The results of this analysis are given in Figure 4.24 and 4.25.

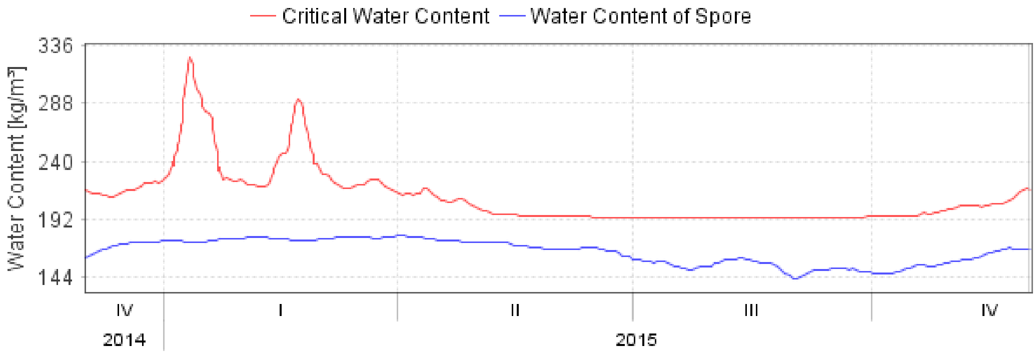


(a)

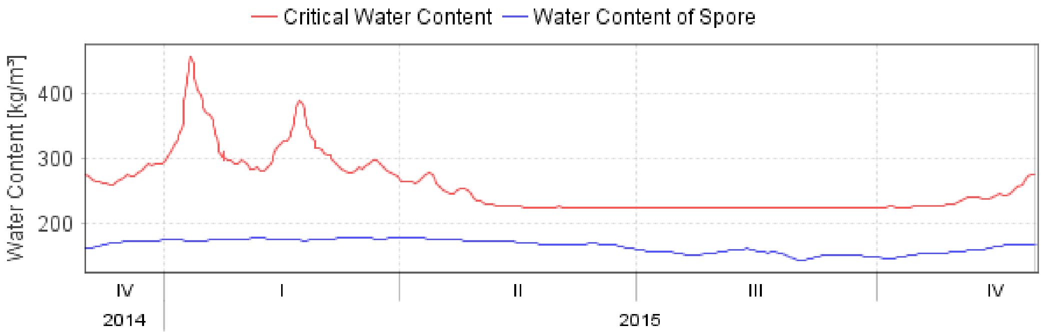


(b)

Figure 4.24. Post-restoration water content results for substrate classes of I (a) and II (b)



(a)



(b)

Figure 4.25. Pre-restoration water content results for substrate classes of I (a) and II (b)

According to these analyses, water content of spore never exceeds the critical water content limit during either pre- and post-restoration periods which corresponds to no risk of mould growth.

4.2. Indoor Air Pollutant Sampling Results

The indoor and outdoor air pollutant samplings for SO_2, NO_2, O_3 and VOC and CO_2 monitoring were done for two week-long periods between the dates of 01.07.2021-08.07.2021 and 08.12.2021-15.12.2021. These dates were chosen to be able to make a direct comparison between the summer and winter concentrations of these air pollutants.

According to these results, the outdoor SO_2 and benzene concentrations were considerably higher compared to the indoor concentrations during winter which is likely due to increased fuel consumption for heating. Conversely, the outdoor O_3 concentrations were higher in summer which is probably because of increased sunlight causing photochemical reactions. Lastly the indoor toluene concentrations were higher than the outdoor concentrations, especially during summer, which indicates an indoor source.

The concentration results of SO_2, NO_2 and O_3 samplings are given in Table 4.5. When measurements are compared to the suggested limit values in the literature, it was found that the SO_2 concentrations of both summer and winter periods were above the 2.7 μg/m^3 limit, the winter concentration of NO_2 was above the 5 μg/m^3 limit and the O_3 concentration during both periods were below the 4 μg/m^3 limit (NAFA, 2016).

Both SO_2 and NO_2 are by-products of burning fossil fuels such as coal, oil and gasoline, so higher outdoor concentrations, especially in winter, are understandable. But the indoor SO_2 concentration result during summer was higher than the outdoor concentration result which indicates an indoor source and should be investigated. Conversely, the source of O_3, especially during summer, is ground-level ozone which forms from photochemical reactions between nitrogen oxides (NO_x) and VOCs (EPA, 2022). According to these results, it is recommended to provide an active filtration solution for NO_2 and especially SO_2.

Table 4.5. Concentrations of sampled SO_2, NO_2 and O_3 for summer and winter periods

μg/m^3	Limit Values	Summer, Indoor	Summer, Outdoor	Winter, Indoor	Winter, Outdoor
Sulfur Dioxide	2.70	34.53	30.80	47.06	90.21
Nitrogen Dioxide	5.00	1.27	8.64	6.94	9.80
Ozone	4.00	0.92	109.86	3.17	41.58

VOCs can be emitted as gases from many sources such as paints, solvents, aerosol sprays, disinfectants and pesticides (EPA, 2022). For measured VOCs, there are not any recommended limit values for the preservation of archival materials outside of keeping their concentrations as low as possible. But when they are investigated from a occupancy health perspective, The National Institute for Occupational Safety and Health (NIOSH) provides recommended exposure limits in 8-hour time weighted averages (TWA). When investigated benzene, toluene, ethylbenzene, p-xylene and m-xylene concentrations were sampled lower than 0.319, 377, 434, 441 and 434 mg/m^3 8-hour TWA limit recommendations of NIOSH, respectively (CDC, 2019). The concentration results of sampled VOCs and their values when converted to 8-hour TWA are given in Table 4.6.

Table 4.6. Concentrations of sampled VOCs for summer and winter periods

µg/m³	Limit Values	Summer, Indoor		Summer, Outdoor		Winter, Indoor		Winter, Outdoor	
		Base	TWA	Base	TWA	Base	TWA	Base	TWA
Benzene	319.00	1.04	21.84	1.07	22.47	4.73	99.33	7.90	165.90
Toluene	377000.00	11.35	238.35	3.79	79.59	10.37	217.77	8.08	169.68
Ethylbenzene	434000.00	0.94	19.74	0.62	13.02	1.00	21.00	1.13	23.73
p-Xylene	441000.00	1.84	38.64	1.17	24.57	1.91	40.11	1.91	40.11
m-Xylene	434000.00	1.59	33.39	0.97	20.37	1.51	31.71	1.48	31.08

The CO_2 monitoring results are given in Figure 4.26 and 4.27. During summer monitoring, the highest measured outdoor CO_2 concentration was 581 ppm, while lowest was 198 ppm and average was 371 ppm. Conversely, the highest measured indoor CO_2 concentration was 498 ppm, while lowest was 357 ppm and average was 400 ppm. Compared to the summer results, the winter results were considerably higher. During winter monitoring, the highest measured outdoor CO_2 concentration was 960 ppm, while lowest was 424 ppm and average was 624 ppm. Conversely, the highest measured indoor CO_2 concentration was 834 ppm, while lowest was 429 ppm and average was 528 ppm. The possible reasons of winter results being higher than summer results can be increased fuel consumption for heating and plants doing more photosynthesis during summer which means more consumed CO_2.

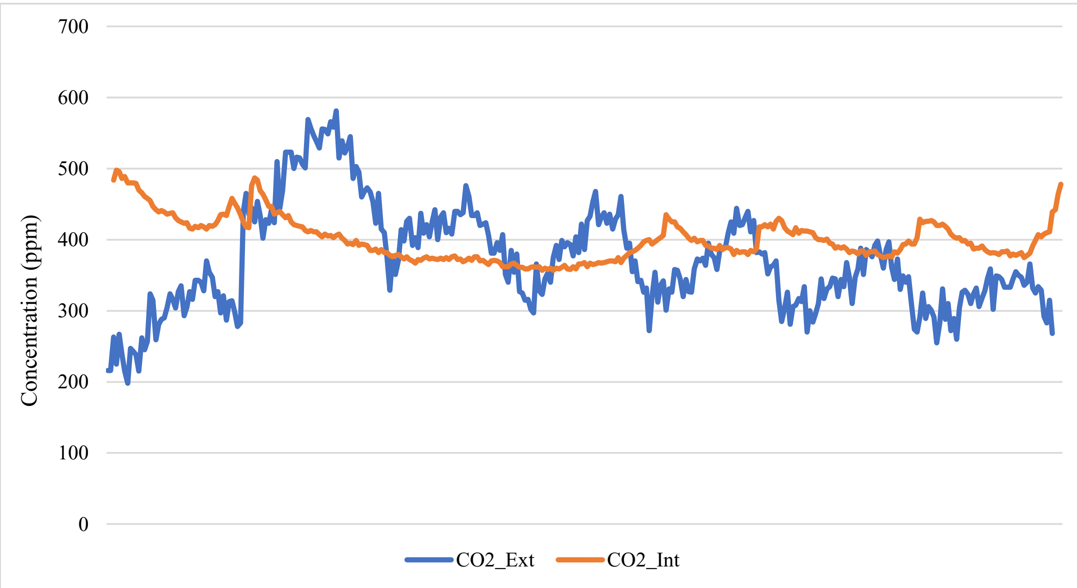


Figure 4.26. CO_2 measurements between 01.07.2021 and 08.07.2021

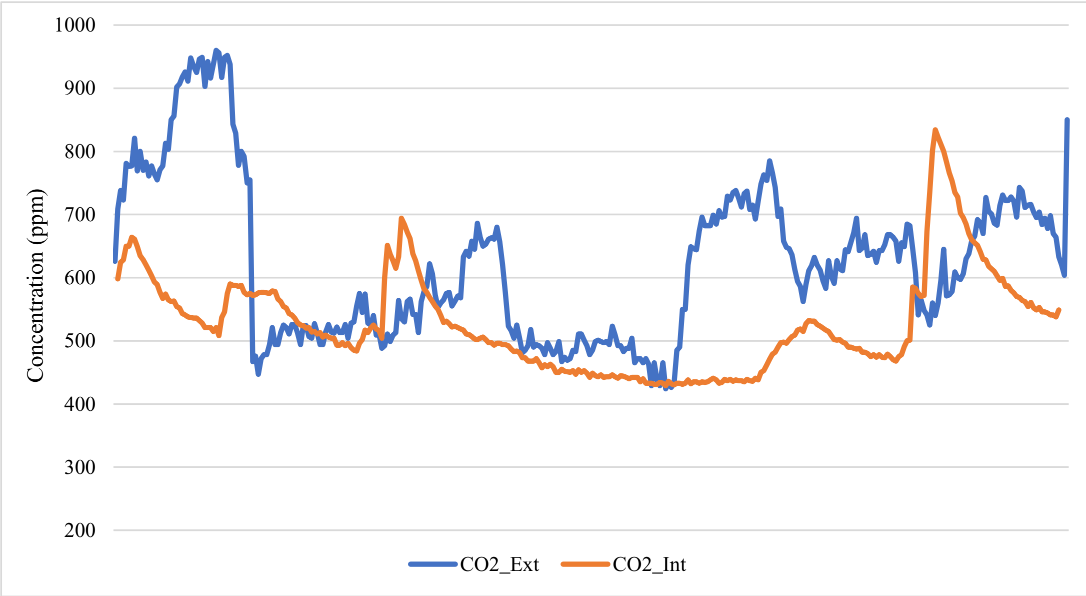
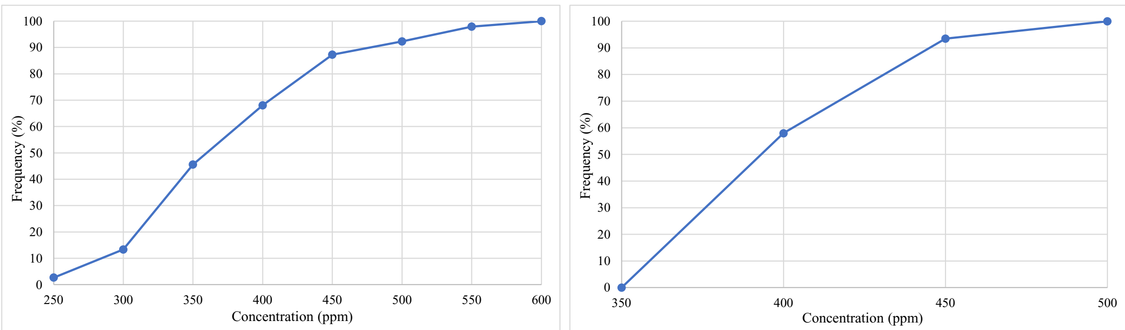


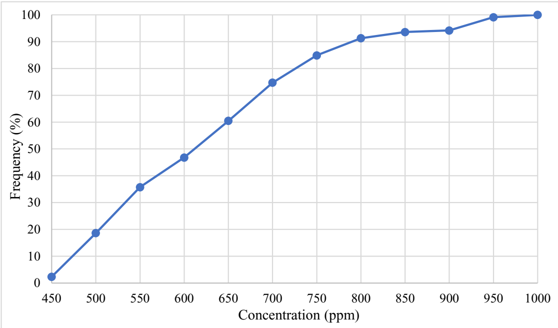
Figure 4.27. CO_2 measurements between 08.12.2021 and 15.12.2021

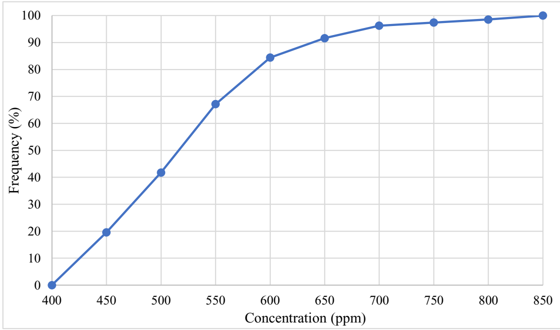
The cumulative frequencies of measured CO_2 concentrations for both periods are given in Figure 4.28 and 4.29. It was found that 100% of the monitored indoor and outdoor CO_2 concentrations were below 600 ppm during summer, while 84.44% of the monitored indoor CO_2 concentrations and 46.80% of the outdoor concentrations were below 600 ppm during winter. According to the limit values in the literature, it is found that both period's results satisfy the IDA 2's range (400-600 ppm) of EN 13799 standard which is classified as the medium indoor air quality (EN, 2006).



(a) (b)

Figure 4.28. Cumulative frequencies of CO_2 measurements for outdoor (a) and indoor (b) between 01.07.2021 and 08.07.2021





(a) (b)

Figure 4.29. Cumulative frequencies of CO_2 measurements for outdoor (a) and indoor (b) between 08.12.2021 and 15.12.2021

4.3. BES Model Calibration Results

The BES model of library was calibrated according to the error determining equations of ASHRAE Guideline 14's which are RMSE and MBE. While the monitored and simulated hourly indoor temperature and relative humidity are compared via these equations, an annual RMSE result below ±30% and a MBE result below ±10% is aimed.

The calibration simulations were ran with using manuscript zone data monitored between 01.01.2020 at 12:00 AM and 01.01.2021 at 12:00 AM by M1 datalogger. After modelling the library's structure, material properties and schedules according to the information obtained from library manager and AutoCAD files, two more calibration simulations were carried out to optimize the HVAC system's temperature and relative humidity settings. HVAC system settings are given in Table 4.7.

Table 4.7. HVAC values for each calibration simulation

	Simulation_1	Simulation_2
Heating	17.50	18.00
Heating Setback	13.50	14.00
Cooling	18.50	18.00
Cooling Setback	20.50	20.00
RH Humidification Setback	50.00	50.00
RH Dehumidification Setback	60.00	60.00
Humidification	On	On
Dehumidification	On	On

The RMSE and MBE results for both simulations' T and RH parameters are given in Table 4.8. The first simulation's annual T results were 4.93% for RMSE and -0.26% for MBE, while the annual RH results were 7.94% for RMSE and -1.70% for MBE. Conversely, the second simulation's annual T results were 5.18% for RMSE and -0.83% for MBE, while the annual RH results were 8.01% for RMSE and -1.71% for MBE. According to these results, both simulations' annual results are within ASHRAE Guideline 14's limits.

While the results are investigated in a monthly basis, RMSE results of May for T of both simulations, RMSE result of April for RH of first simulation and November and December results for RH of both simulations were higher than ±10% which is high, but still within the guideline's limit. For November and December months, MBE results for RH of both simulations were higher than the guideline's ±10% limit (Table 4.8). The periods which HVAC system was under maintenance and monitored T fluctuating because of this can be given as the reason of high T results. Conversely, the reason of high RH results is because of simulated RH data fluctuating a lot less than the monitored data. According to these results, the HVAC settings of Simulation 1 was chosen as the HVAC options of the final calibrated model.

Table 4.8. RMSE and MBE results for each simulation

%	T-RMSE		T-MBE		RH-RMSE		RH-MBE	
	Sim_1	Sim_2	Sim_1	Sim_2	Sim_1	Sim_2	Sim_1	Sim_2
January	1.93	1.09	-1.86	0.95	6.59	6.62	-5.77	-5.97
February	2.14	1.07	-1.92	0.69	7.41	7.26	-4.55	-5.58
March	2.03	1.07	-1.31	0.85	8.42	8.98	-5.14	-6.54
April	3.27	1.22	2.37	1.12	10.09	9.61	-7.42	-6.62
May	10.26	10.80	-0.80	-3.49	4.50	4.14	-0.85	0.20
June	3.18	2.06	2.40	-0.28	2.81	2.89	2.37	2.64
July	7.44	8.59	-2.14	-4.79	7.38	7.51	6.69	6.78
August	6.78	7.80	-1.47	-4.14	8.29	8.38	7.76	7.89
September	3.29	3.22	-1.40	-1.25	6.17	6.33	5.88	6.15
October	2.40	2.56	1.22	-1.51	2.92	3.15	2.15	2.75
November	3.44	4.55	0.82	1.62	11.59	11.67	-10.75	-10.82
December	2.08	1.64	-1.70	1.10	11.93	12.52	-10.71	-11.77
Annual	4.93	5.18	-0.26	-0.83	7.94	8.01	-1.70	-1.71

4.4. Future Climate Simulation Results

Figure 4.30 and 4.31 show the outdoor simulated T and RH results for December 2019-November 2020, December 2049-November 2050 and December 2079-November 2080. From these results it was found that the T values during 2050 will generally be around 2°C higher than 2020, while the T values during 2080 will be around 1.5°C higher than 2050. Comparatively, the RH values during 2050 will generally be around 2% lower than 2020, while the RH values during 2080 will be around 0.5% lower than 2050.

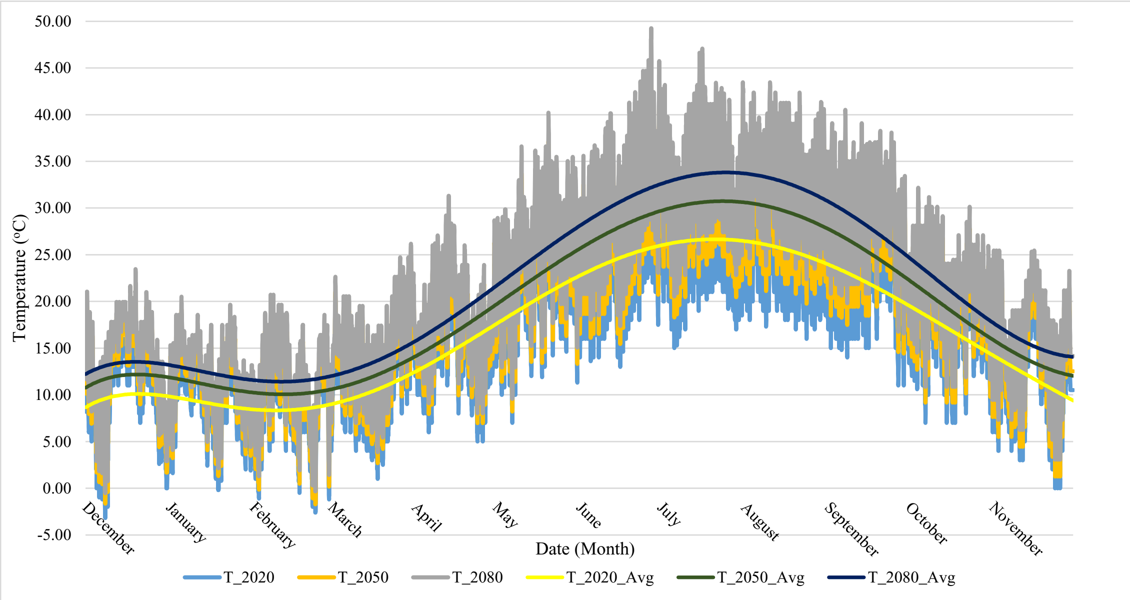


Figure 4.30. Temperature results of outdoor for 2019-2020, 2049-2050 and 2079-2080

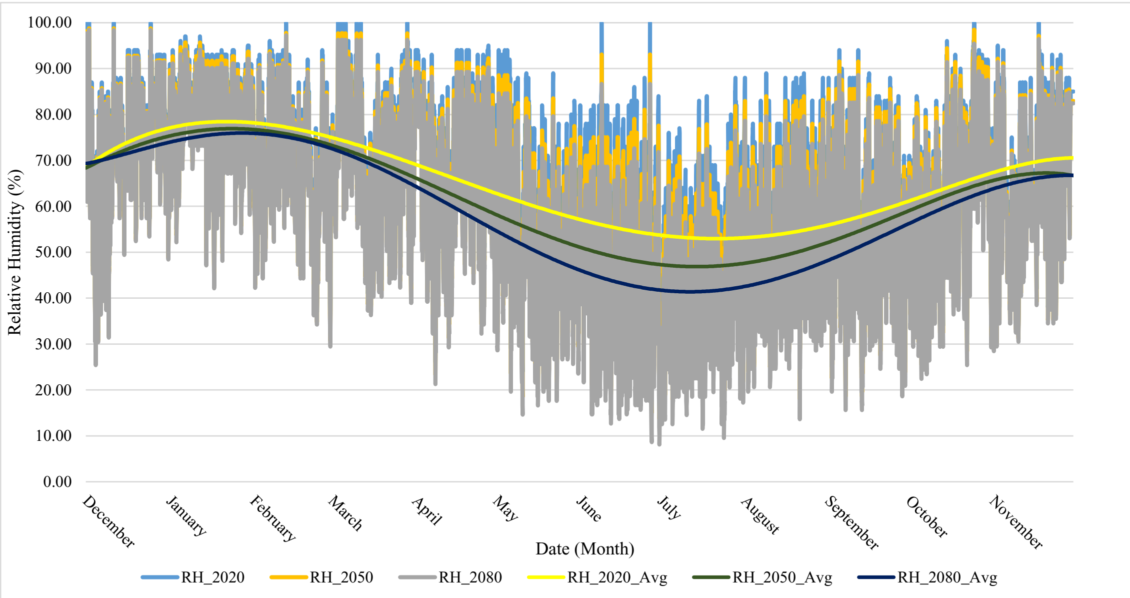


Figure 4.31. Relative humidity results of outdoor for 2019-2020, 2049-2050 and 2079-2080

To investigate the future indoor climate of the library, the simulated T and RH results of manuscript zone for December 2049-November 2050 and December 2079-

November 2080 were compared to the monitored T and RH results of December 2019-November 2020. The comparison of these three periods are given in Figure 4.32 and 4.33.

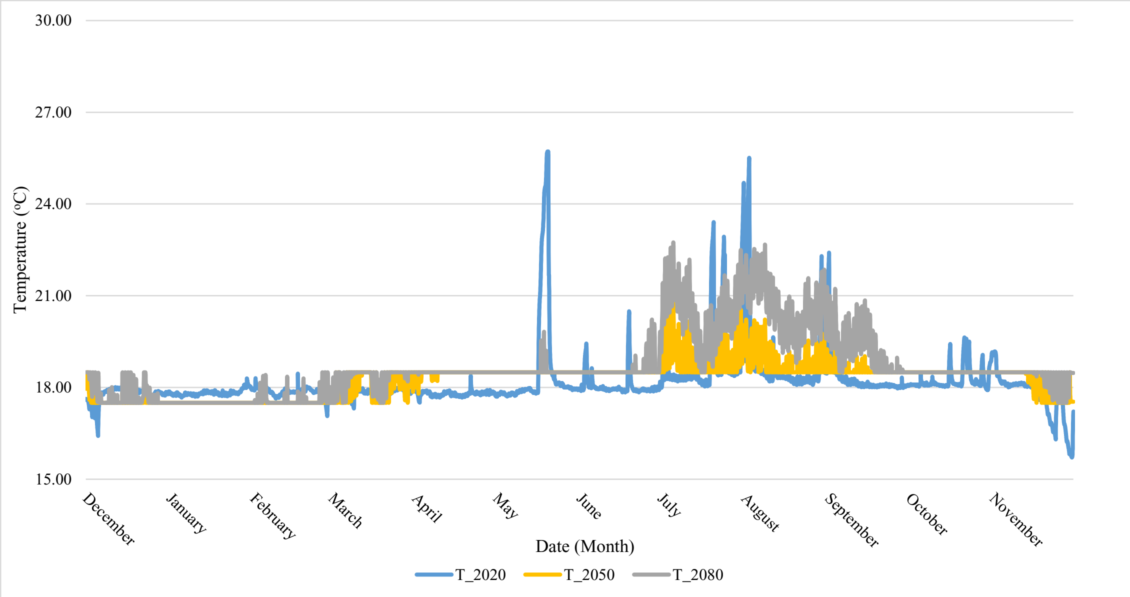


Figure 4.32. Temperature results of manuscript zone for 2019-2020, 2049-2050 and 2079-2080

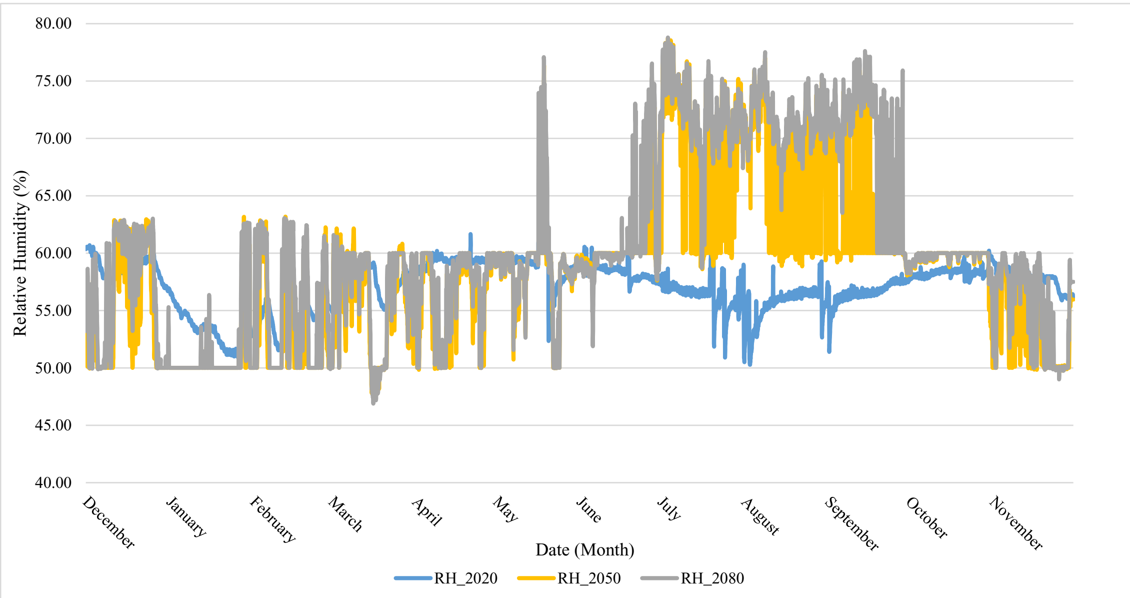


Figure 4.33. Relative humidity results of manuscript zone for 2019-2020, 2049-2050 and 2079-2080

The comparative results show that the indoor temperature of the library will be similar to the measured T results of December 2019-November 2020 during winter months by the years of 2050 and 2080. But between June and October months, more frequent and severe fluctuations are observed compared to December 2019-November 2020, especially during 2080, because of HVAC system's settings not being able to fully mitigate the increased outdoor temperatures due to climate change. Conversely, the simulated RH results for both 2050 and 2080 show even more frequent and severe fluctuations for all months except January, June and October.

The highest, lowest and average of manuscript zone's T and RH values in a monthly basis and annual results for three period are given in Table 4.9. During 2019-2020, the highest measured T was 25.72°C, lowest T was 15.71°C and average was 18.15°C. The highest measured RH was 63.07%, lowest RH was 50.27% and average was 57.06%. During 2049-2050, the highest simulated T was 20.75°C, lowest T was 17.50°C and average was 18.26°C. The highest simulated RH was 78.73%, lowest RH was 47.36% and average was 58.33%. Lastly, during 2079-2080, the highest simulated T was 22.75°C, lowest T was 17.50°C and average was 18.67°C. The highest simulated RH was 78.78%, lowest RH was 46.89% and average was 60.36%.

Table 4.9. Maximum, minimum and average of manuscript zone's T and RH values in a monthly basis and annual values for 2019-2020, 2049-2050 and 2079-2080

T (°C)	2019-2020			2049-2050				2079-2080			
	Min	Max	Avg	Min	Max	Avg	Diff_Avg	Min	Max	Avg	Diff_Avg
December	16.42	18.01	17.76	17.50	18.50	17.56	-0.21	17.50	18.50	17.72	-0.05
January	17.67	18.30	17.83	17.50	17.50	17.50	-0.33	17.50	17.50	17.50	-0.33
February	17.07	18.45	17.87	17.50	17.97	17.51	-0.36	17.50	18.50	17.60	-0.27
March	17.31	18.15	17.85	17.50	18.50	18.07	0.22	17.50	18.50	18.32	0.47
April	17.51	18.38	17.79	17.80	18.50	18.48	0.69	18.42	18.50	18.50	0.71
May	17.70	25.72	18.65	18.50	18.50	18.50	-0.15	18.50	19.83	18.53	-0.12
June	17.84	20.50	18.05	18.50	19.04	18.51	0.45	18.50	20.22	18.60	0.54
July	17.99	24.69	18.90	18.50	20.75	18.97	0.07	18.50	22.75	20.44	1.54
August	18.08	25.51	18.78	18.50	20.22	18.84	0.06	18.80	22.67	20.64	1.86
September	17.97	22.41	18.24	18.50	19.30	18.53	0.29	18.50	21.23	19.21	0.98
October	17.91	19.63	18.28	18.50	18.50	18.50	0.22	18.50	18.50	18.50	0.22
November	15.71	19.18	17.70	17.50	18.50	18.11	0.41	17.50	18.50	18.37	0.67
Annual	15.71	25.72	18.15	17.50	20.75	18.26	0.11	17.50	22.75	18.67	0.52

RH (%)	2019-2020			2049-2050				2079-2080			
	Min	Max	Avg	Min	Max	Avg	Diff_Avg	Min	Max	Avg	Diff_Avg
December	56.68	60.69	58.75	49.93	62.96	54.94	-3.81	49.88	63.01	56.49	-2.26
January	50.95	56.79	53.28	50.00	63.16	50.83	-2.44	50.00	62.67	51.15	-2.13
February	51.52	56.03	54.21	50.00	63.18	53.03	-1.18	49.90	63.05	54.92	0.71
March	54.82	59.53	57.15	47.36	62.16	55.70	-1.45	46.89	61.59	56.45	-0.70
April	58.09	61.66	59.26	49.83	60.01	55.90	-3.36	50.00	60.01	57.02	-2.24
May	52.34	63.07	58.85	50.00	76.36	58.29	-0.56	50.00	77.07	59.05	0.20
June	56.64	60.92	58.40	56.05	75.29	60.30	1.90	51.89	76.53	61.52	3.12
July	50.88	60.94	56.47	58.60	78.73	68.86	12.39	58.69	78.78	72.08	15.61
August	50.27	59.28	55.59	58.84	77.01	67.27	11.69	63.75	77.51	71.56	15.97
September	51.39	58.21	56.57	58.05	76.14	61.96	5.39	58.23	77.62	69.12	12.55
October	57.43	60.21	58.38	50.31	60.00	59.54	1.16	55.33	60.00	59.70	1.32
November	55.88	59.43	57.74	49.77	59.97	52.89	-4.85	49.00	60.00	55.01	-2.73
Annual	50.27	63.07	57.06	47.36	78.73	58.33	1.27	46.89	78.78	60.36	3.31

4.4.1. Future General Climate Risk Assessment

According to the simulation results of December 2049-November 2050 and December 2079-November 2080, indoor climate of Tire Necip Paşa Library's manuscript zone was analyzed according to AA, A1 and A2 climate control classes of ASHRAE Chapter 23. The analysis results showed that either periods' indoor climate did not satisfy the bandwidth limits of any climate control classes except 2049-2050 results for A2 climate control class while December 2019-November 2020 results satisfied the AA climate control class.

The results for climate control class of AA are given in Figure 4.33 and 4.35. Figure 4.34 shows the results of 2049-2050 which 100% of T results and 58% of RH results were within the bandwidths which resulted in a 58% overall result. Comparatively, Figure 4.35 shows the results of 2079-2080. According to 2079-2080 simulation, 99% of T results and 51% of RH results were within the bandwidths which resulted in a 51% overall result.

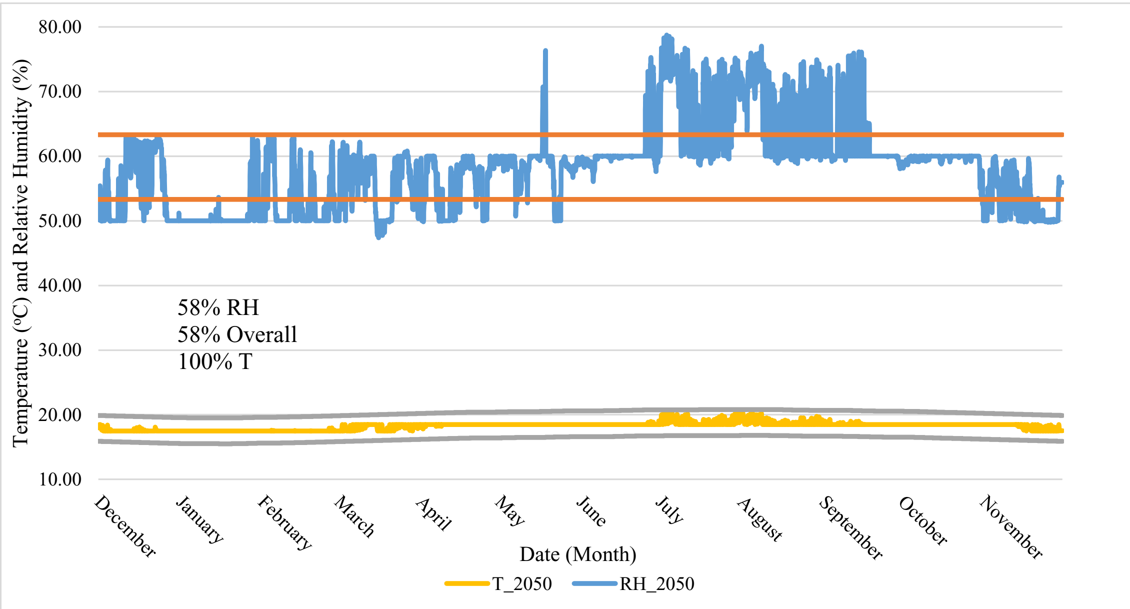


Figure 4.34. Temperature and relative humidity results for 2049-2050 with AA control class bandwidths

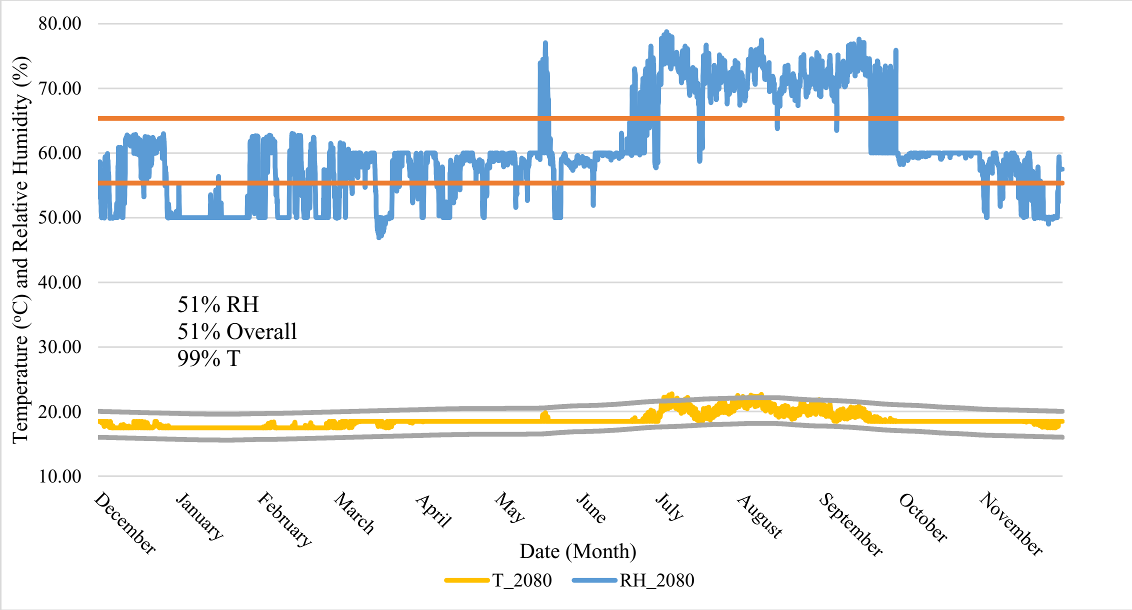


Figure 4.35. Temperature and relative humidity results for 2079-2080 with AA control class bandwidths

The results for A1 climate control class are given in Figure 4.36 and 4.37. Figure 4.36 shows the results of 2049-2050 simulation which shows that 100% of T and 76% of RH results were within the bandwidths, resulting in a 76% overall result. Comparatively, Figure 4.37 shows the results of 2079-2080 simulation which shows that 99% of T and 75% of RH results were within the bandwidths which resulted in a 74% overall result.

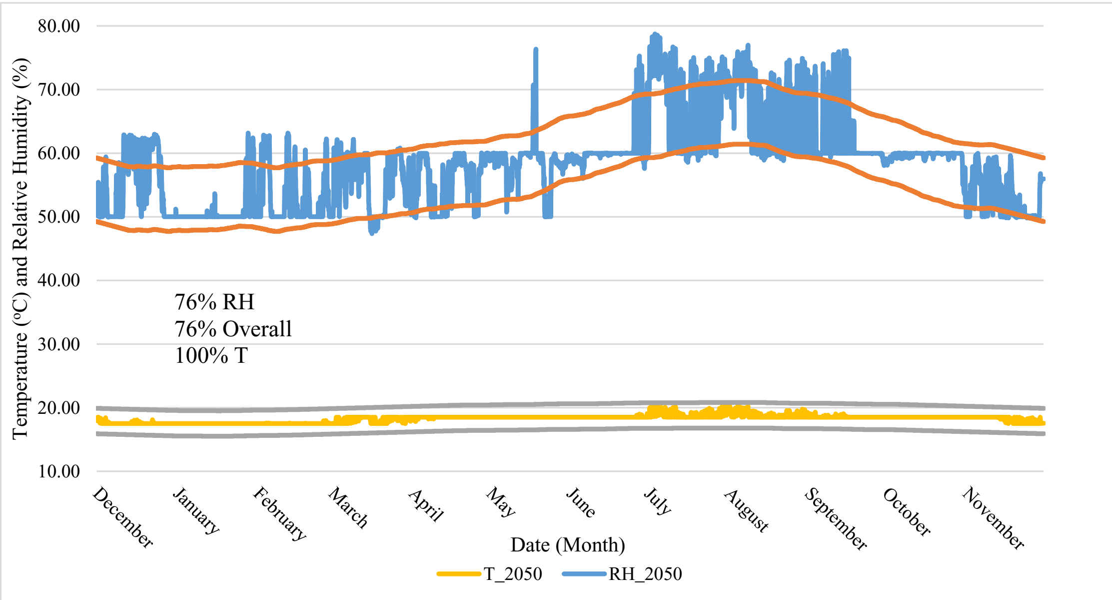


Figure 4.36. Temperature and relative humidity results for 2049-2050 with A1 control class bandwidths

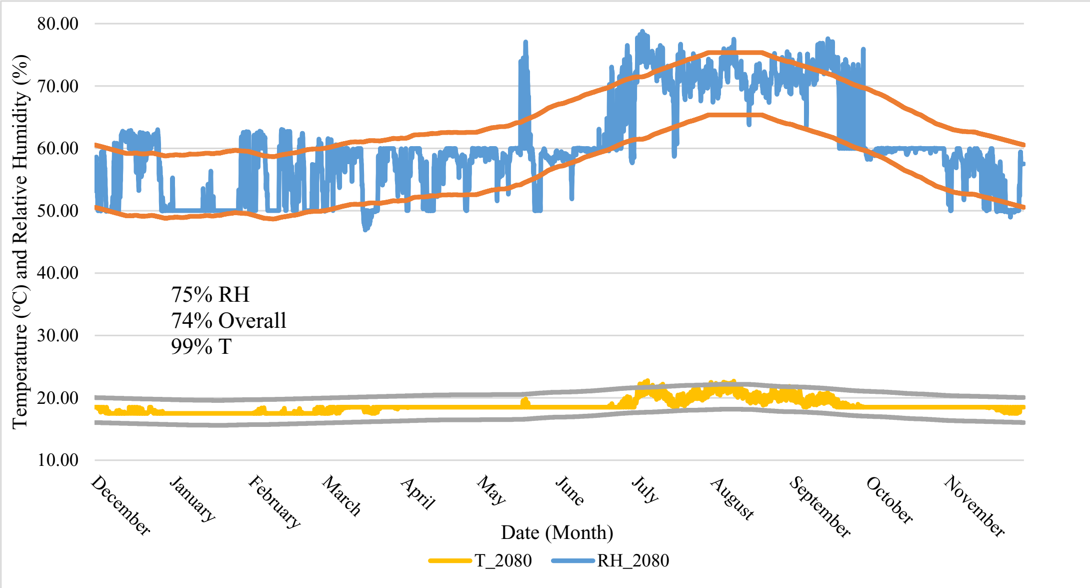


Figure 4.37. Temperature and relative humidity results for 2079-2080 with A1 control class bandwidths

Lastly, results for climate class of A2 are given in Figure 4.38 and 4.39. Figure 4.38 shows the results of 2049-2050 simulation which shows that 100% of T results and 88% of RH results were within the bandwidths which resulted in a 88% overall result. Comparatively, Figure 4.39 shows the results of 2079-2080 simulation which shows that 99% of T results and 64% of RH results were within the bandwidths which resulted in a 64% overall result.

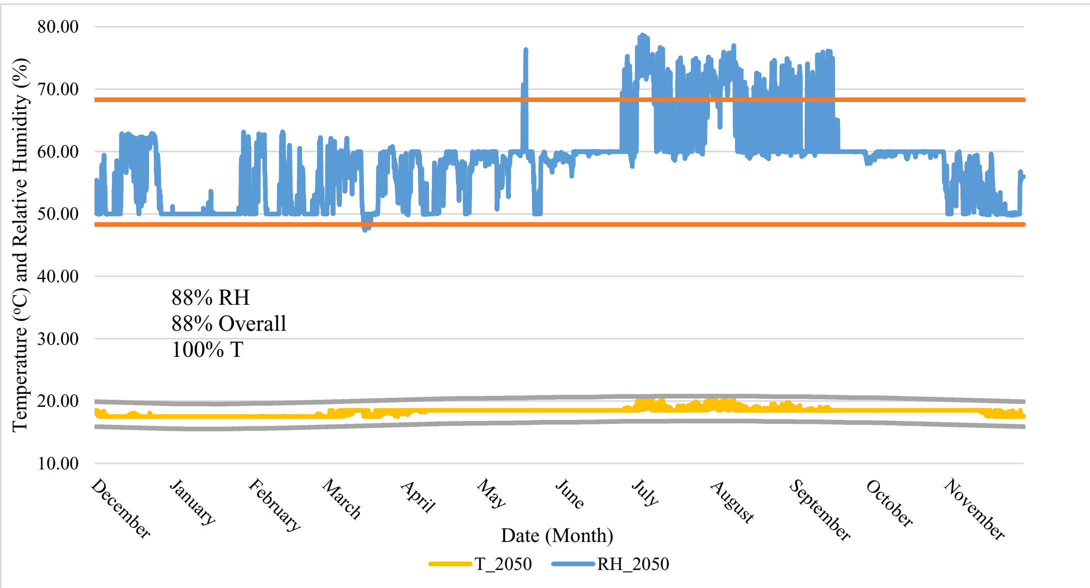


Figure 4.38. Temperature and relative humidity results for 2049-2050 with A2 control class bandwidths

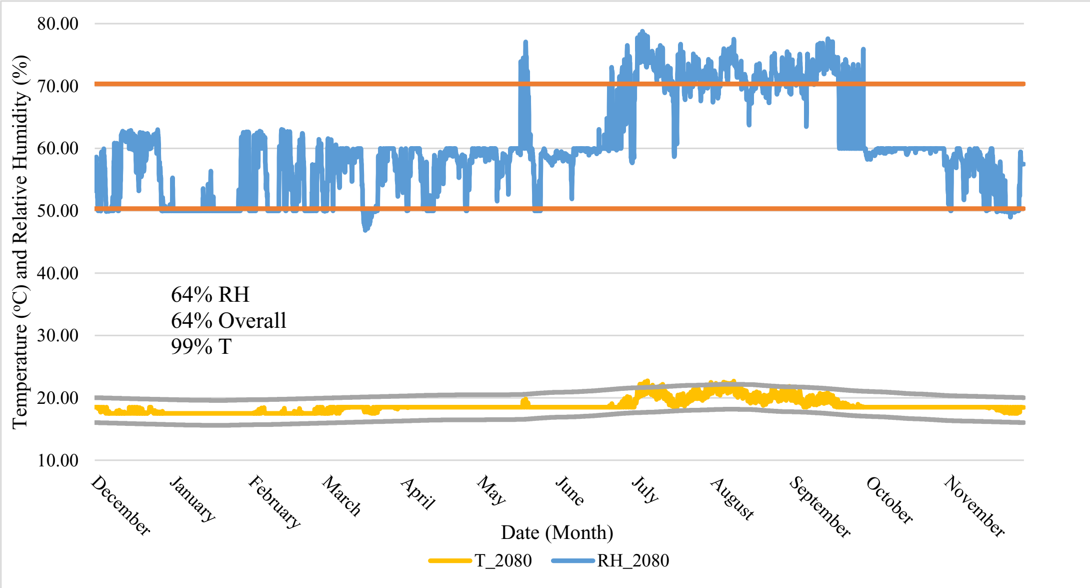


Figure 4.39. Temperature and relative humidity results for 2079-2080 with A2 control class bandwidths

When all results are investigated, the 2049-2050 results for A2 climate control class is the only result which satisfy its' respective climate control class's bandwidth limits. Conversely, the 2079-2080 results could not manage to satisfy any control classes' bandwidth limits and the best result for this period were for A1 climate control class.

When results of both periods for three control classes are investigated in a monthy basis according to Table 4.10, T results for all months of both periods show satisfactory results for all climate control classes. All T results of 2049-2050 were 100%, while the lowest T result of 2079-2080 period was 92.61% for July month for all three climate control classes.

For AA climate control class, the best RH results for both periods were for October followed by June and May. Conversely, the lowest RH result for both periods was for January with a 8.87% result for 2049-2050 and a 9.27% result for 2079-2080. The RH results for A1 climate control class were far better compared to AA climate control class results. The best results belonged to January, October, April and May months. Lastly, the RH results of 2049-2050 for A2 climate control class were better than A1 climate control class results, while the 2079-2080 results were worse. All months of 2049-2050 except July and August showed good RH results for A2 climate control class. Conversely, the best months of 2079-2080 were April, May, June and October, while other months could not manage to satisfy the bandwidth limits with the lowest month being January with a result of 15.19%.

Table 4.10. Temperature and relative humidity results of 2049-2050 and 2079-2080 simulations according to climate classes' bandwidths on a monthly basis (cont. on next page)

%	AA					
	T_2050	T_2080	RH_2050	RH_2080	Ov_2050	Ov_2080
December	100.00	100.00	50.40	57.80	50.40	57.80
January	100.00	100.00	8.87	9.27	8.87	9.27
February	100.00	100.00	32.18	44.25	32.18	44.25
Winter	100.00	100.00	30.45	36.95	30.45	36.95
March	100.00	100.00	71.64	70.83	71.64	70.83
April	100.00	100.00	70.83	76.53	70.83	76.53
May	100.00	100.00	89.52	82.53	89.52	82.53
Spring	100.00	100.00	77.40	76.63	77.40	76.63
June	100.00	100.00	94.31	82.22	94.31	82.22
July	100.00	92.61	25.54	2.15	25.54	2.15
August	100.00	94.89	31.72	0.27	31.72	0.27
Summer	100.00	95.79	50.05	27.63	50.05	27.63
September	100.00	100.00	81.11	27.64	81.11	27.64
October	100.00	100.00	99.33	99.87	99.33	99.87
November	100.00	100.00	39.58	55.14	39.58	55.14
Autumn	100.00	100.00	73.63	61.31	73.63	61.31
Overall	100.00	98.94	57.91	50.64	57.91	50.64

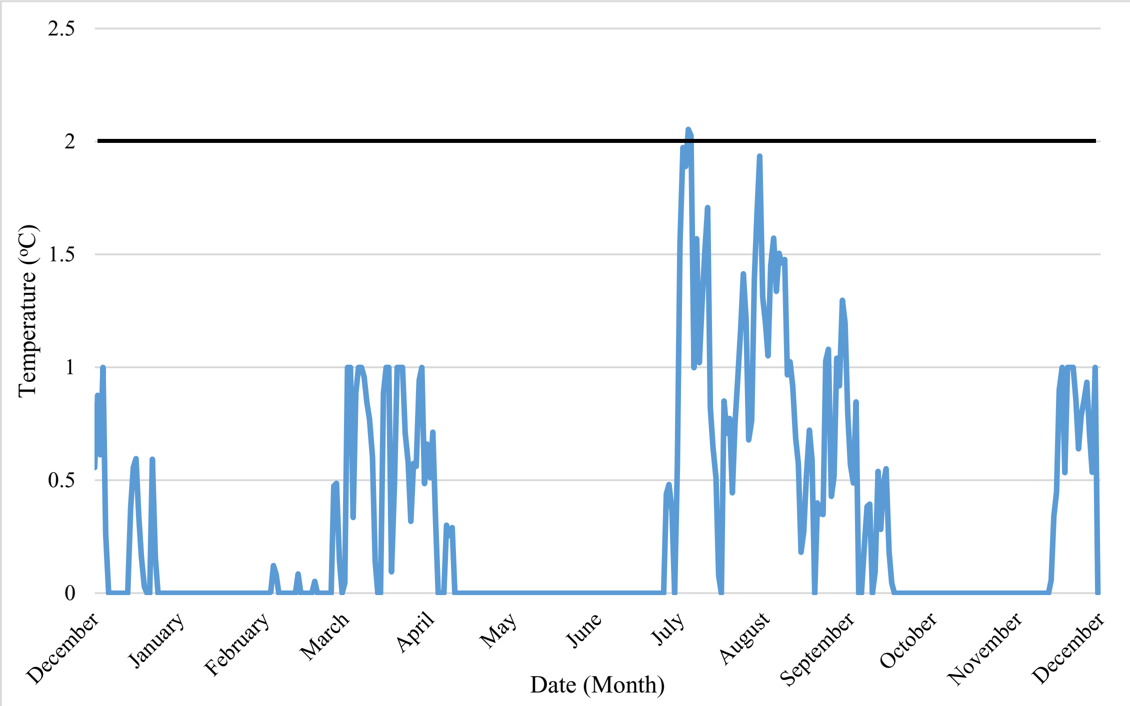
%	A1					
	T_2050	T_2080	RH_2050	RH_2080	Ov_2050	Ov_2080
December	100.00	100.00	66.26	54.57	66.26	54.57
January	100.00	100.00	93.95	92.74	93.95	92.74
February	100.00	100.00	83.05	69.54	83.05	69.54
Winter	100.00	100.00	81.04	72.34	81.04	72.34
March	100.00	100.00	69.09	77.28	69.09	77.28
April	100.00	100.00	80.14	84.72	80.14	84.72
May	100.00	100.00	89.52	84.14	89.52	84.14
Spring	100.00	100.00	79.57	82.02	79.57	82.02
June	100.00	100.00	92.92	74.44	92.92	74.44
July	100.00	92.61	30.51	62.77	30.51	61.96
August	100.00	94.89	45.16	93.41	45.16	90.99
Summer	100.00	95.79	55.80	76.90	55.80	75.82
September	100.00	100.00	87.36	41.11	87.36	41.11
October	100.00	100.00	99.87	94.09	99.87	94.09
November	100.00	100.00	72.36	67.36	72.36	67.36
Autumn	100.00	100.00	86.68	67.81	86.68	67.81
Overall	100.00	98.94	75.73	74.80	75.73	74.52

Table 4.10 (cont.)

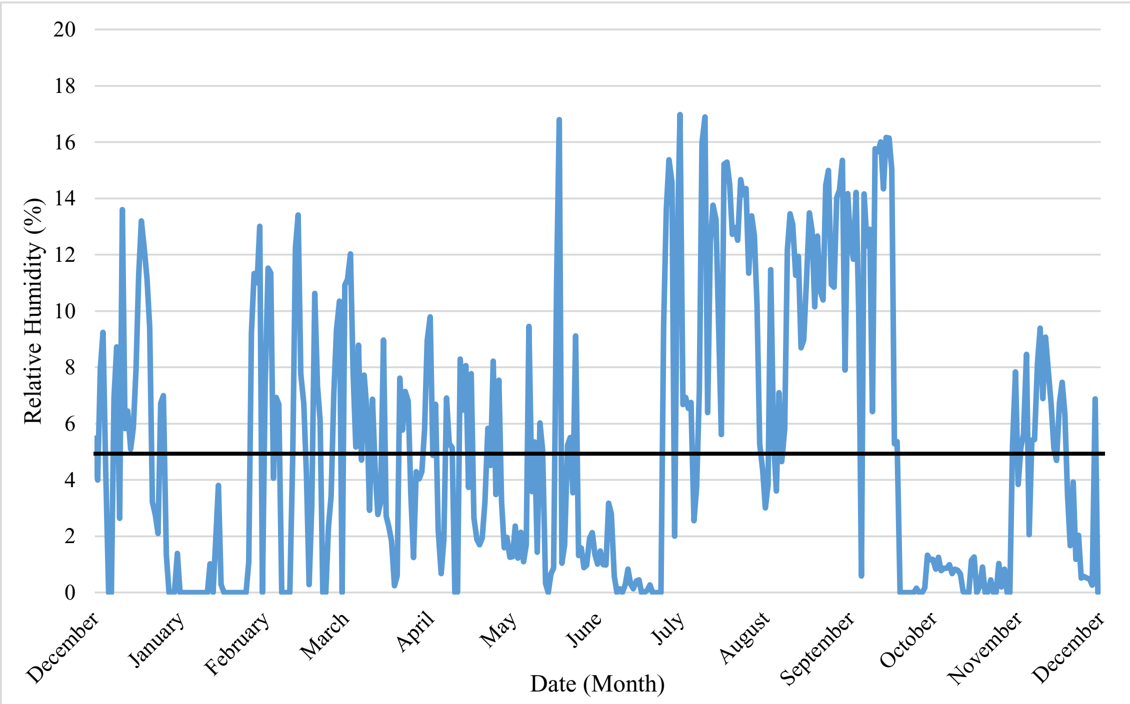
%	A2					
	T_2050	T_2080	RH_2050	RH_2080	Ov_2050	Ov_2080
December	100.00	100.00	100.00	77.15	100.00	77.15
January	100.00	100.00	100.00	15.19	100.00	15.19
February	100.00	100.00	100.00	61.93	100.00	61.93
Winter	100.00	100.00	100.00	51.19	100.00	51.19
March	100.00	100.00	97.31	79.70	97.31	79.70
April	100.00	100.00	100.00	90.28	100.00	90.28
May	100.00	100.00	99.19	90.99	99.19	90.99
Spring	100.00	100.00	98.82	86.96	98.82	86.96
June	100.00	100.00	95.56	88.89	95.56	88.89
July	100.00	92.61	34.41	21.77	34.41	21.77
August	100.00	94.89	45.43	29.70	45.43	29.30
Summer	100.00	95.79	58.06	46.33	58.06	46.20
Septembe	100.00	100.00	86.39	37.64	86.39	37.64
October	100.00	100.00	100.00	100.00	100.00	100.00
November	100.00	100.00	100.00	73.89	100.00	73.89
Autumn	100.00	100.00	95.51	70.83	95.51	70.83
Overall	100.00	98.94	88.05	63.84	88.05	63.81

4.4.2. Future Mechanical Degradation Risk Assessment

Figure 4.40 shows the maximum daily T and RH differences of December 2049-November 2050 simulations. When investigated, almost all of the daily T fluctuations were below the ±2 K limit, while only half of the daily RH fluctuations were below ±5% limit. Figure 4.41 shows the cumulative frequencies of maximum daily T and RH differences, respectively. According to the cumulative frequency calculations, 99.47% of the 2049-2050 T differences were below ±2 K limit, while 53.82% of the RH differences were below ±5% RH limit.

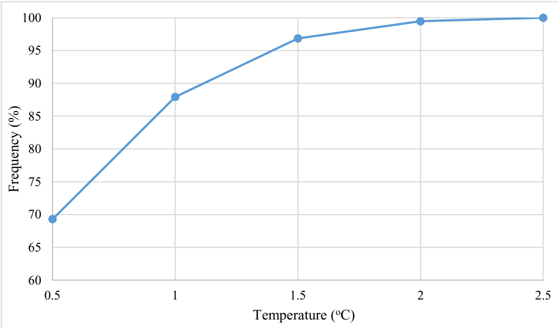


(a)

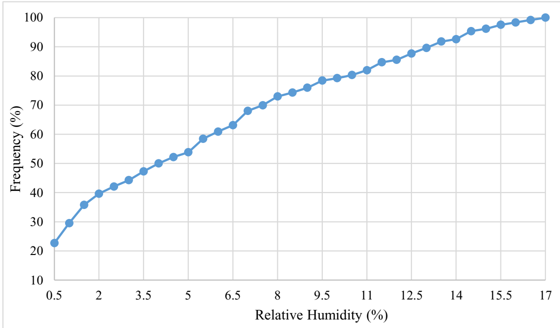


(b)

Figure 4.40. Maximum daily T (a) and RH (b) differences of 2049-2050



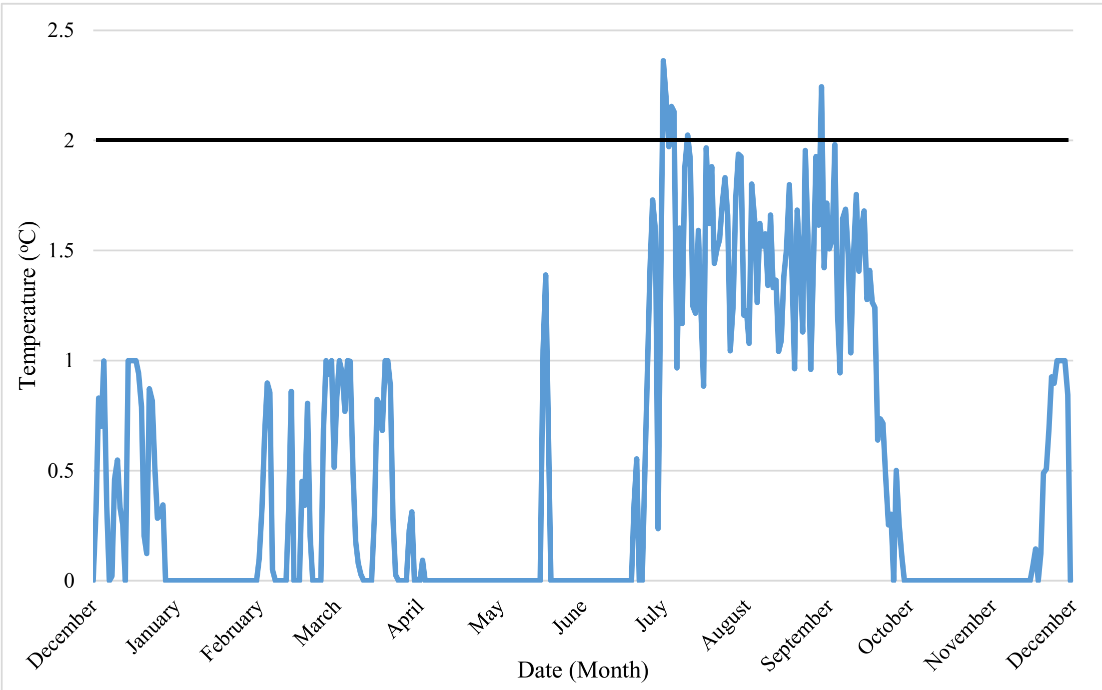
(a)



(b)

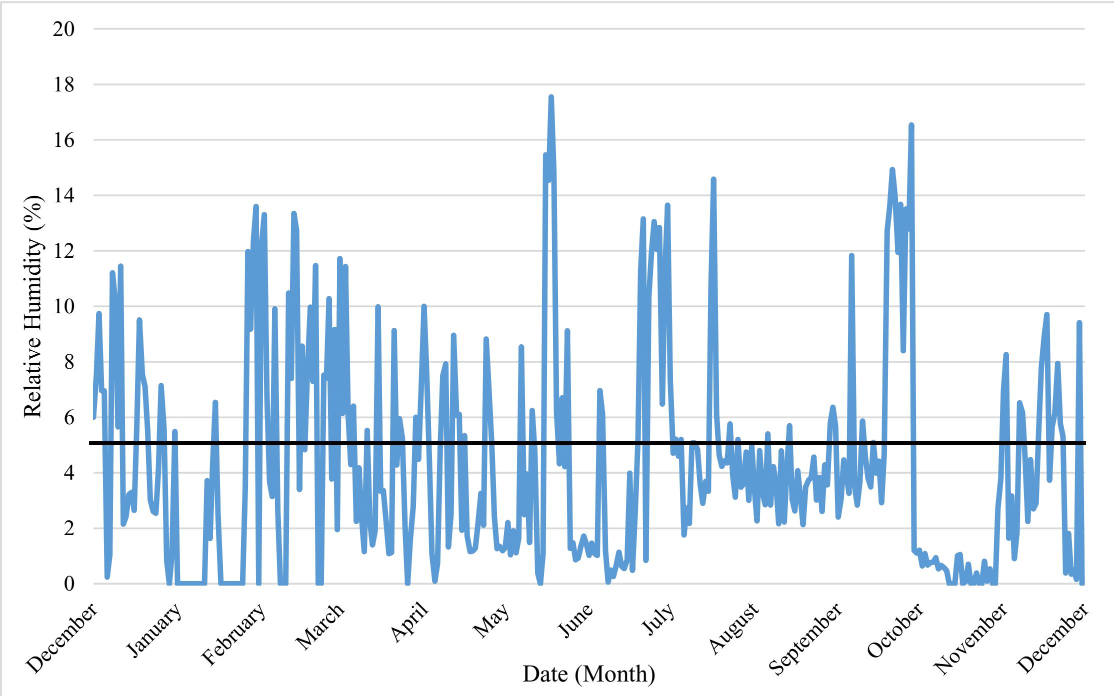
Figure 4.41. Cumulative frequencies of T (a) and RH (b) differences of 2049-2050

Conversely, Figure 4.42 shows the maximum hourly T and RH differences of December 2079-November 2080 simulations. While most of the monitored hourly T fluctuations were below the ±2 K limit, a significant amount of RH fluctuations were over ±5% limit. Figure 4.43 shows the cumulative frequencies of maximum daily T and RH differences, respectively. According to the cumulative frequency calculations, 98.42% of the 2079-2080 daily T differences were below ±2 K limit which is similar to 2049-2050 results, while 65.57% of the RH differences were below ±5% RH limit which is better than 2049-2050 results. According to these results, it can be said that there will be a considerable risk of mechanical degradation during both periods.



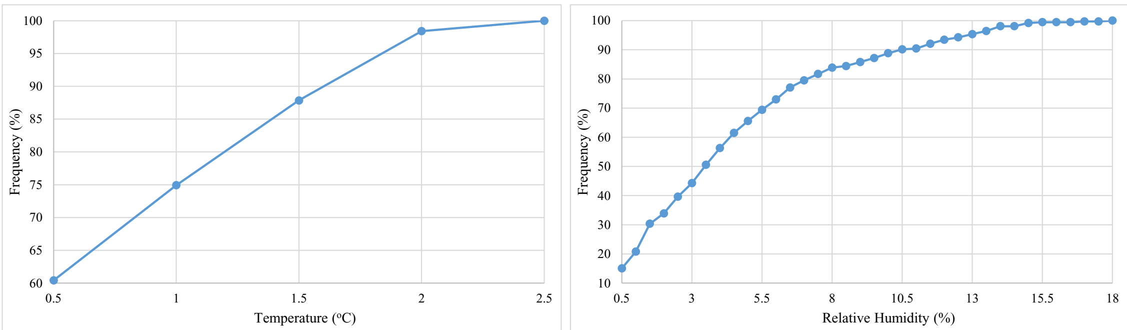
(a)

Figure 4.42. Maximum daily T and RH differences of 2079-2080 (cont. on next page)



(b)

Figure 4.42 (cont.)



(a) (b)

Figure 4.43. Cumulative frequencies of T (a) and RH (b) differences of 2079-2080

4.4.3. Future Chemical Degradation Risk Assessment

The results of the chemical degradation risk assessment of manuscript zone based on the December 2049-November 2050 and December 2079-November 2080 simulations' T and RH data in terms of LM can be found in Figure 4.44. According to 2049-2050 data, the manuscripts will be under low risk of chemical degradation with a calculated eLM value of 1.03. The lowest calculated LM value was 0.50 in July, while the highest was 1.50 in March. The 2079-2080 data show that manuscripts will be under medium risk of chemical degradation with a calculated eLM value of 0.91. The lowest calculated LM value was 0.38 in July, while the highest was 1.48 in March. The most risky periods for both simulations were between June and October while other months show low risk of chemical degradation.

When compared, these results are slightly worse than December 2019-November 2020 period's eLM result of 1.08, while they are far better than December 2014-November 2015 period's eLM result of 0.54.

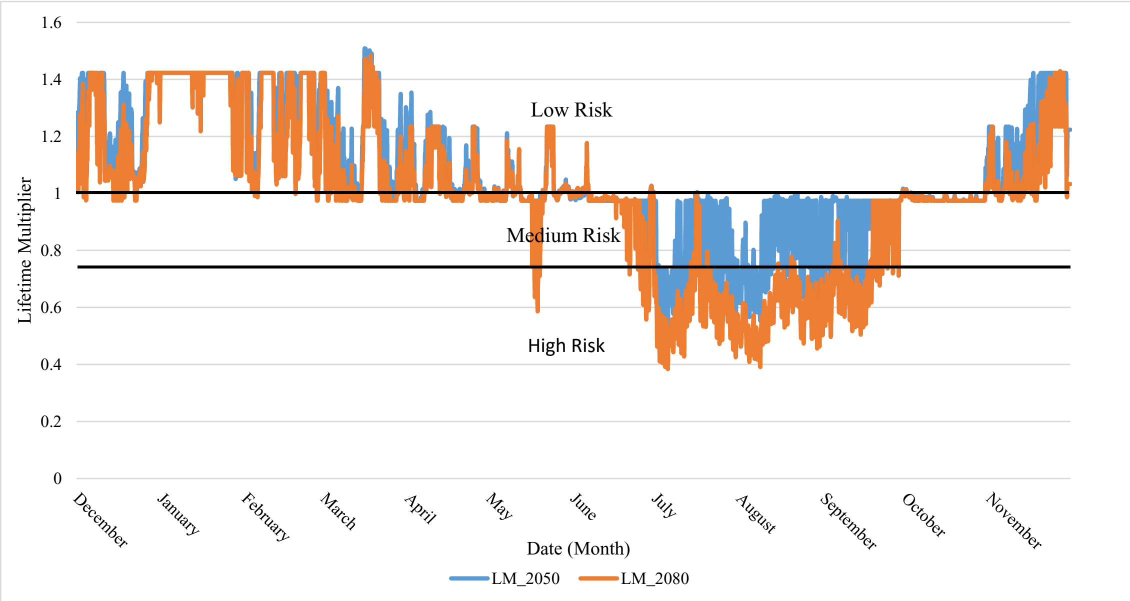


Figure 4.44. LM values of the manuscript zone for 2049-2050 and 2079-2080

4.4.4. Future Biological Degradation Risk Assessment

Similar to the December 2014-November 2015 and December 2019-November 2020 assessments, the biological degredation risk assessment of manuscript zone for December 2049-November 2050 and December 2079-November 2080 were done with the use of isopleths and superimposing the simulated T and RH data to limit curves. Results of this assessment can be seen in Figure 4.45 and 4.46. According to these results, there will be no risk of biological degradation in either 2049-2050 or 2079-2080 and MRF was 0.00.

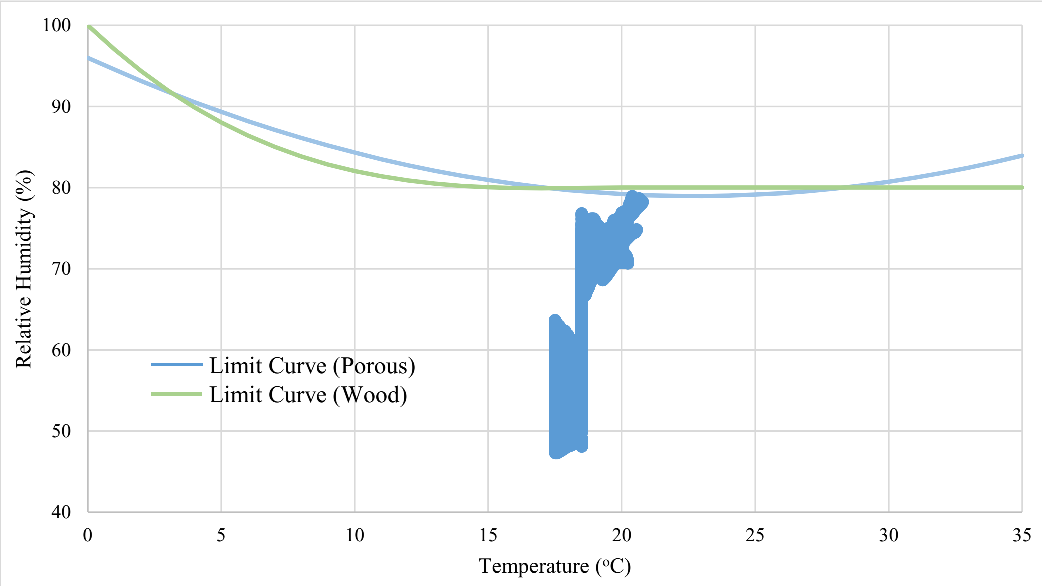


Figure 4.45. Mould growth risk of the manuscript zone for 2049-2050

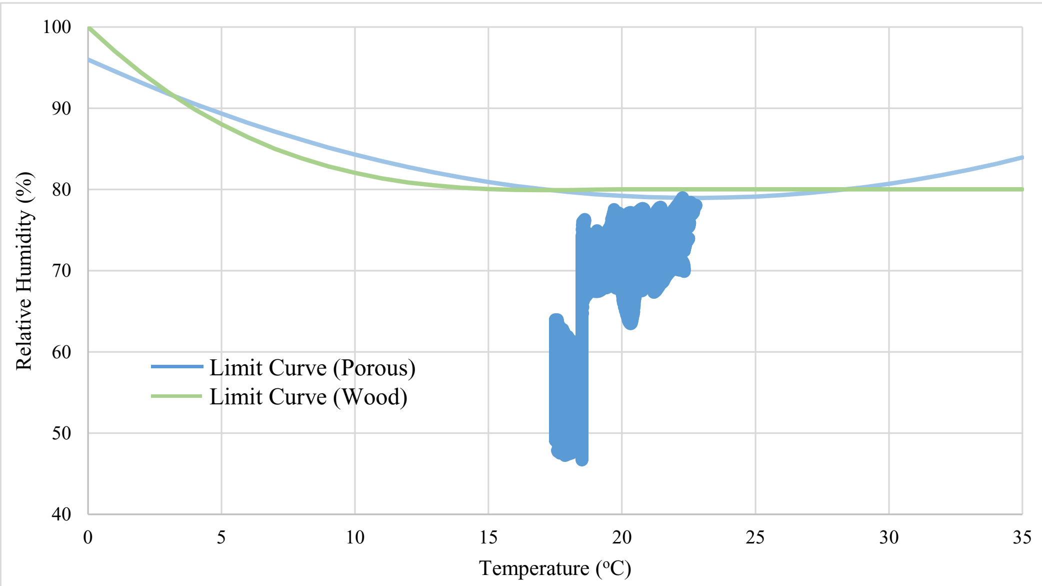
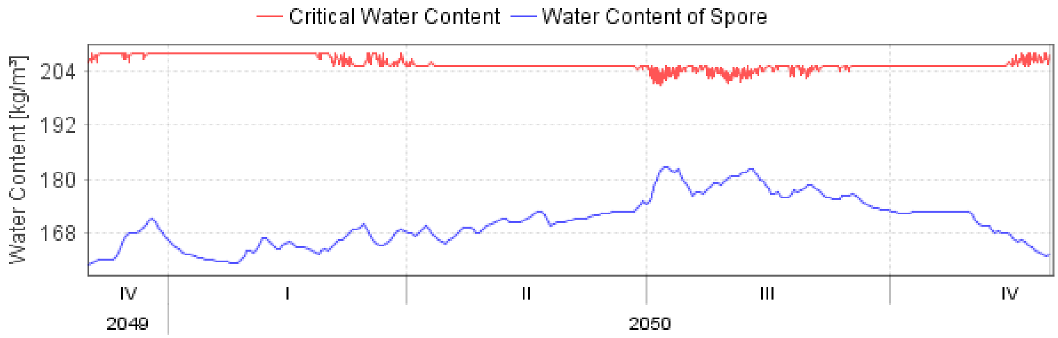
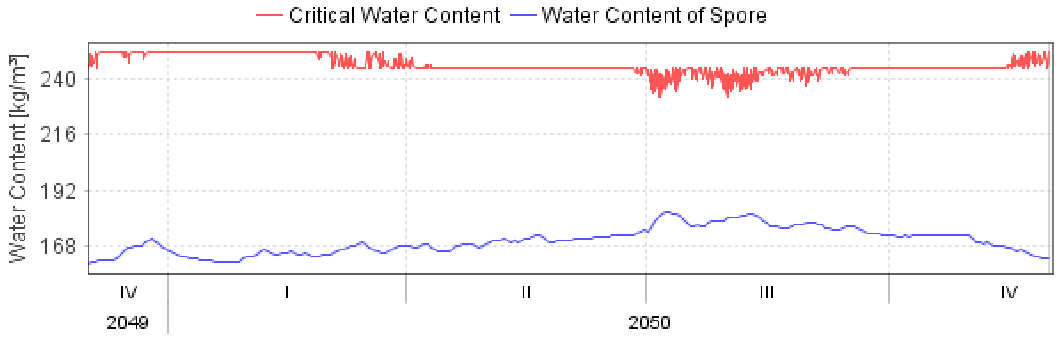


Figure 4.46. Mould growth risk of the manuscript zone for 2079-2080

The simulated data of December 2049-November 2050 and December 2079-November 2080 periods were also analyzed in WUFI-Bio according to the Sedlbauer's substrate classes of I and II. The substrate class I is used for substrates such as wall paper, plaster boards and bio-degradable building materials, while the substrate class II is used for less bio-utilizable substrates like plasters, mineral based materials and wood products. The results of this analysis are given in Figure 4.47 and 4.48, and according to these results water content of spore never exceeds the critical water content limit during either periods which corresponds to no risk of mould growth.

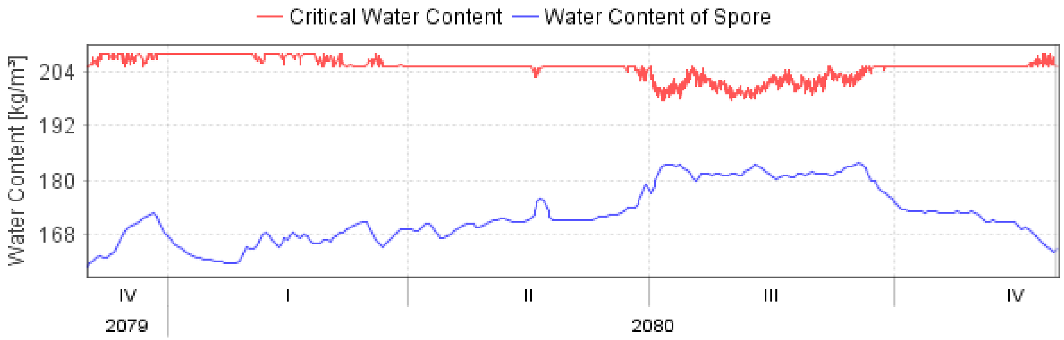


(a)

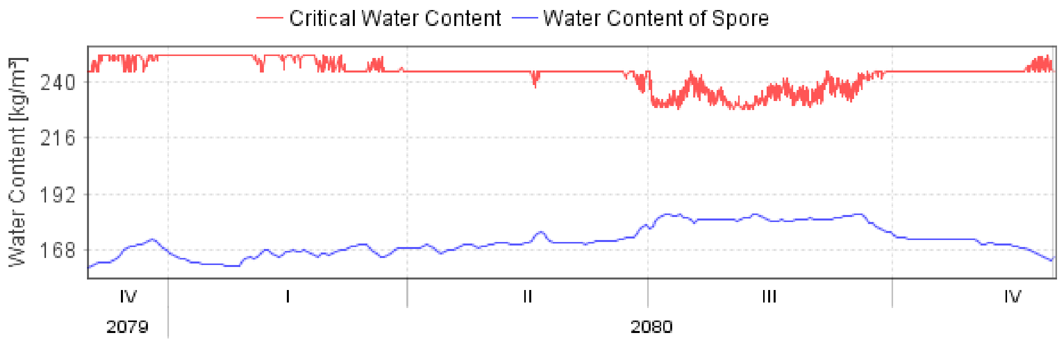


(b)

Figure 4.47. 2049-2050 water content results for substrate classes of I (a) and II (b)



(a)



(b)

Figure 4.48. 2079-2080 water content results for substrate classes of I (a) and II (b)

4.5. Discussion

When analysis results are investigated as a whole, it can be said that the HVAC system installation improved the current indoor climate of Tire Necip Paşa Library in terms of manuscript preservation. But analysis results also show that improvements will be needed or the HVAC system's settings will need to be customized accordingly on future, since the HVAC system will not be able to provide an as stable indoor climate as it does currently with its' current settings due to the ongoing climate change. If improvements or changes are not made, it was seen that the degradation risks of manuscripts will be higher.

While December 2014-November 2015 results were monitored, the library was still naturally ventilated and had a free-floating hygrothermal behavior. When the monitored data was analyzed, it was seen that indoor climate of the library at that period did not satisfy either AA, A1 or A2 climate control classes of ASHRAE Chapter 23 with the best overall result being 60% for A1 climate control class. A considerable amount of mechanical degradation risk was observed because of 13.9% of the daily RH differences being above ±5% RH limit. An eLM value of 0.54 was calculated which corresponds to high chemical degradation risk. Lastly, the biological degradation risk was not observed.

After the restoration process and HVAC system installation, the December 2019-November 2020 monitoring showed far better results compared to the pre-restoration results. The indoor climate of library in this period managed to satisfy the AA climate control class. The calculated eLM value was 1.08 which corresponds to low chemical degradation risk and mechanical or biological degradation risk were not observed.

During this period, the indoor and outdoor air pollutant samplings and CO_2 monitoring were also done during two periods in summer and winter. The results showed that the SO_2 concentrations were above 2.7 μg/m^3 limit during both periods, while the winter NO_2 concentration was above 5 μg/m^3 limit and the O_3 concentration during both periods were below 4 μg/m^3 limit (NAFA, 2016). Benzene, toluene, ethylbenzene, p-xylene and m-xylene concentrations during both periods were below respectively 0.319, 377, 434, 441 and 434 mg/m^3 8-hour TWA limits which are provided by NIOSH (CDC, 2019). Lastly, the monitored CO_2 values were generally below 600 ppm during both periods which classifies the indoor climate of the library as IDA 2 according to EN 13799 standard which corresponds to the medium indoor air quality (EN, 2006).

The simulated December 2049-November 2050 results showed that the indoor climate of library satisfied A2 climate control class with an overall result of 88%. Significant mechanical degradation risk was observed due to 46.18% of the daily RH differences being above ±5% RH limit. While the calculated eLM value was 1.03 which corresponds to low risk of chemical degradation, months between June and October were found to be moderate to highly risky in terms of chemical degradation. Conversely, the biological degradation risk was not observed.

Lastly, the simulated December 2079-November 2080 results could not manage to satisfy any of AA, A1 and A2 climate control classes while the highest overall result was 74% for A1 climate control class. The mechanical degradation risk was observed due to 34.43% of the RH differences being above ±5% RH limit. The calculated eLM value during this period was 0.91 which corresponds to medium risk of chemical degradation. Similarly to 2049-2050 results, the months between June and October were found out to be moderate to highly risky months during this period. Lastly, no risk of biological degradation was observed.

The results of future climate simulations showed that while T values were within the HVAC's 17.5-18.5°C heating and cooling settings during eight months, the cooling setting of 18.5°C is continuously exceeded during June, July, August and September months with higher fluctuations during the 2079-2080 period compared to the 2049-2050 period. While these fluctuations were within ±2 K limit for mechanical degradation, the simulated values were as high as 20.75°C during 2049-2050 and 22.75°C during 2079-2080 which increase the risk of chemical degradation. Because of this reason, the HVAC system's heating, cooling and setback settings should be lowered accordingly between June and September months to compensate for higher than average outdoor temperatures.

Conversely, it was seen that the RH values continuously fluctuated between 50-60% humidification and dehumidification setback settings during eight months, while they exceeded the 60% dehumidification setback value during June, July, August and September months. During these months, the simulated RH values were as high as 78.73% and 78.78% for respectively 2049-2050 and 2079-2080 periods which increase the chemical degradation risk. The RH fluctuations also continuously exceeded ±5% limit during entirety of both periods which increase the mechanical degradation risk. Because of these reasons, a tighter HVAC humidification-dehumidification setback range should be adopted for all months and additional dehumidification measures should be taken between June and September months on future.

CHAPTER 5

CONCLUSION

Indoor climate of Tire Necip Paşa Library was analyzed during four periods: December 2014-November 2015, December 2019-November 2020, December 2049-November 2050 and December 2079-November 2080. 2014-2015 and 2019-2020 years as pre- and post-restoration periods were compared to assess the past indoor climate of the library which was naturally ventilated and the current indoor climate of the library which is regulated by the HVAC system. Besides, 2049-2050 and 2079-2080 periods were compared to 2019-2020 period to assess the future indoor climate of the library and impact of climate change on library's indoor climate. Lastly various air pollutants were sampled and CO_2 was monitored during summer and winter of 2021 to find out if the concentrations of these air pollutants are below the limit values defined by international standards. Two different seasons were chosen to conduct these measurements to investigate the seasonal concentration differences.

The comparative results of 2014-2015 and 2019-2020 showed that HVAC system greatly improved the indoor climate of library in terms of the preservation of manuscripts. The mechanical degradation risk is eliminated. The chemical degradation risk is reduced to low from high risk. Library's indoor climate also satisfies the bandwidths of AA climate control class of ASHRAE Chapter 23 (2011), while it did not manage to satisfy either AA, A1 or A2 control class in 2014-2015.

Conversely, it was found that HVAC system will struggle to provide a balanced and stable indoor climate in 30 years with its' current settings which will be even less stable in 60 years. The reason is that ongoing climate change will create a less stable indoor climate with higher fluctuations. Therefore, a high risk of mechanical degradation will be observed on future. Besides, the chemical degradation risk will be higher compared to 2019-2020 results. Consequently, HVAC settings should be customized accordingly on future to compensate for changes in climate.

Lastly, indoor SO_2 concentrations during both seasons and indoor NO_2 concentration during winter were above the limit values which indicate the need for an active filtration measure. Indoor CO_2 concentrations during both seasons were within IDA 2 category's ranges which is a satisfactory result.

5.1. Recommendations

Following recommendations can be made to minimise the degradation risks in Tire Necip Paşa Library, and other similar libraries or archival buildings:

- While the results show that HVAC system installation improved the indoor climate of the library, HVAC system's continuous operation is essential to prevent T and RH fluctuations which can result in degradation risks if HVAC shortages continue for prolonged durations. HVAC system generally turns itself off during summer months due to high temperatures increasing the internal pressure of exterior unit of the system. The reason of this is the exterior unit directly being exposed to sunlight. Thus, an easy to implement solution can be covering the exterior unit with a shading element. Additionally a building automation system or a system which allows the remote control of HVAC system can be installed to be able to turn on the HVAC system when it turns itself off while the occupants of library are away.
- Continuous monitoring of the library environment and analyzing the monitored data periodically is required to assure that HVAC system operates correctly, and the preservation conditions do not deteriorate. Monitoring the T and RH parameters of the main hall of library with at least two dataloggers which should be placed to the interior and exterior of manuscript cage is essential. Additionally, another datalogger can be placed to outdoors to compare indoor and outdoor climates. Monthly or yearly monitoring reports should be prepared from monitoring results. These reports should be archived to be able to analyze the indoor climate at a yearly basis and for future reference if needed.
- Manuscripts should only be read in the library area to protect them against fluctuations which can occur if they are moved to office area of the library which has a different and less stable indoor climate.
- HVAC system will struggle to provide a stable indoor climate on future due to climate change with its' current settings. Thus, HVAC settings should be

customized accordingly to maintain the stable indoor climate of the library. Heating and cooling set temperatures, and setback temperatures should be lowered as needed to compensate the higher than average temperatures between the months of June and September. A tighter humidification-dehumidification range should be set for all months, and this range should be lowered for the months between June and September.

- If changing HVAC system's settings does not be enough to compensate for future climate change, additional measures can be taken such as taking additional dehumidification measures, improving HVAC system's capacity, and reducing air transfer between office area and main hall. However, they should be taken without harming the heritage value of Tire Necip Paşa Library itself.
- The windows of the main hall are the building components which have the most impact on heat and moisture transfer from exterior to interior. Therefore, weather stripping in a regular basis as needed is essential to reduce the impact of outdoor weather on indoor climate.
- Sampled SO_2 and NO_2 concentrations showed that the filtration of the indoor air of library is necessary to protect the library's paper-based collection against specific air pollutants which may infiltrate into the main hall from outside air.
- While ASHRAE Chapter 23 and other guidelines used in this thesis are recognized worldwide and useful to make a general assessment of any indoor climate, developing a national standard for archival interiors is still required to make more accurate assessments according to the regional climatic zones and unique cultural assets of Turkey, and to provide an easily accessible source for only-Turkish readers.

5.2. Future Studies

Since future climate analysis results showed that indoor climate of the library will deteriorate on future and degradation risks will increase, further studies on Tire Necip Paşa Library can be about testing the effect of different envelope and air conditioning based solutions on the future indoor climate via simulation software. In addition to impact on degradation risks, these solutions can also be investigated from the aspects of implementation costs and energy consumption.

While the envelope of office area was improved in restoration process, it has a far less stable indoor climate compared to main hall of the library, since it is not constantly regulated by the HVAC system. Therefore, the office area undoubtedly has an impact on the indoor climate of the main hall due to air infiltration between spaces even though openings between spaces are constantly kept closed. The future simulation based studies can be carried out to investigate the interaction between the climates of office area and main hall. If the interaction is found out to be significantly impactful on the indoor climate of the main hall, various solutions can be tested via simulation software to lower the interaction between two spaces.

While scope of this thesis was investigating the preservation conditions of manuscripts in Tire Necip Paşa Library, the ornaments on the interior walls of the main hall of library also have significant heritage values, and need to be preserved. Thus a future research can focus on the impact of indoor climate on the preservation conditions of these ornaments. If the ornaments are found out to be under a significant degradation risk, additional measures should be tested, and taken to ensure their preservation.

This thesis shows that with proper monitoring and use of analysis methods which can be found in the literature, it is possible to investigate similar libraries' indoor climates and degradation risk of their collections. Therefore, similar degradation risk analyses for more libraries can be carried out on future with using the methodology of this thesis.

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