Influence of microclimate control scenarios on energy consumption in the Gallery of the 19th-Century Polish Art in the Sukiennice (the former Cloth Hall) of The National Museum in Krakow

A Sadłowska-Sałęga[1], J Radoń[1], J Sobczyk[2], K Wąs[1]

[1] Faculty of Environmental Engineering and Land Surveying, University of Agriculture in Krakow, al. A. Mickiewicza 24-28, 30-059 Krakow, Poland
[2] Laboratory of Analysis and Non-Destructive Investigation of Heritage Objects (LANBOZ), National Museum in Krakow, al. 3 Maja 1, 30-062 Krakow, Poland

Abstract. The main aim of preventive conservation, ensuring protection of historic collections, is stabilization of relative humidity, and for some materials also temperature, in the interiors of historic buildings or museums. The improper microclimatic parameters may cause irreversible damages. On the other hand, strict control of indoor climate is expensive. Definition of optimal microclimate control in terms of energy use, taking into account most important, sometimes even contradictory factors, requires interdisciplinary cooperation, among others in the field of conservation, collections' care, architecture, building physics and HVAC systems. Due to the type of historic objects and specific microclimate requirements, hygrothermal simulations of whole historical buildings are essential for the most part of a case study. The paper presents an analysis of energy consumption according to various microclimate control scenarios for The National Museum in Kraków: The Gallery of 19th-Century Polish Art - located in Renaissance Cloth Hall in Kraków (UNESCO World Heritage Site). The analysis is based on the results of simulations performed with WUFI®PLUS software and in situ measurements. The microclimate control variants were developed, among others, on the basis of ASHRAE and ICOM-IIC guidelines. The research was supported by The Polish National Centre for Research and Development within "HERIVERDE" project.

1. Introduction

The main activity of preventive conservation, ensuring protection of historic collections, is stabilization of relative humidity, and for some materials also temperature, in the interiors of historic buildings or museums. The improper microclimatic parameters may cause irreversible damages. On the other hand, strict control of indoor climate is expensive both in the stage of investment in the installation of air conditioning systems as well as the current operation of these devices. The microclimate inside museum should also ensure, if possible, thermal comfort for the people.

Relative humidity is, according to scientific publications and international standards [1, 2], the most important parameter responsible for the formation of physical damage, especially in objects composed of complex hygroscopic organic materials, i.e. paintings, furniture, etc. Fluctuations of relative humidity cause a dimensional response of organic hygroscopic materials which can lead to the formation of looses, cracks, etc. Relative humidity accelerates the natural aging processes of objects. Higher values of relative humidity significantly affect the acceleration of metal corrosion processes. They also are conducive to the growth of microorganisms. It can be assumed that reduction of relative humidity by half reduces the rate of chemical degradation by more than half [3].

The temperature also influences the acceleration of aging processes. It can be assumed that a 5°C increase in temperature doubles the rate of chemical degradation [3]. Temperature in the range of 20 ÷ 30°C favors the growth of microorganisms [4].

On the basis of many years of research, institutions dealing with heritage protection have developed guidelines regarding permissible temperature and relative humidity changes in museums. The most restrictive approach to microclimate control in museums, archives and libraries presents American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). The maximum fluctuations and gradients are divided into 5 basic control classes for general collections. In addition, separate control classes have been distinguished for collections containing chemically unstable materials and metal collections [5]. In 2014, International Council of Museums (ICOM-CC) and International Institute for Conservation of Historic and Artistic Works (IIC) announced a joint declaration regarding the requirements for microclimate control in museum facilities. Two ranges of fluctuations in temperature and relative air humidity were developed depending on the type of collections: general collections and containing hygroscopic materials [6]. Some museum institutions, for example the National Museum in Krakow (MNK), developed their own guidelines for the specifity of stored exhibits or the constructions of buildings in which museums are located. Examples of guidelines of these institutions are presented in the Table 1.

Present paper is a step forward into an idea of “green museum” which comprises of safety of heritage objects, thermal comfort of visitors and staff, environment protection and energy saving [7].

The Sukiennice (the former Cloth Hall) is a large market hall erected in the 13th century in the middle of the Market Square, extended in the 14th century in the Gothic style and remodelled in the mid-16th century after Renaissance fashion. Following its restoration in the years 1875 ÷ 1879, it began to serve a representative function and became a venue for grand balls and patriotic celebrations. Due to their location and character, the halls on the first floor of the Cloth Hall building became the first seat of the National Museum in Krakow. In the years 2006 ÷ 2010, the building was thoroughly renovated.

The museum has eight air-conditioning units which implement four scenarios of microclimate control (depending on the way the room is used). The building also has central heating and a floor heating system (in exhibition halls), which is switched on if necessary.
The exhibition in the Cloth Hall is presented in the following four rooms: The Bacciarelli Room, The Michałowski Room, The Siemiradzki Room, The Chełmoński Room.

2. WUFI®plus model of the building

Calculations of microclimate and energy demand in the Cloth Hall in Krakow were made using the WUFI®plus software. Program developed by the Fraunhofer Institute for Building Physics, allows realistic calculation of the transient coupled one- and two-dimensional heat and moisture transport in walls and other multi-layer building components exposed to natural weather. The program has been widely validated on the basis of many years experimental research including historical buildings [8, 9].

The Cloth Hall model was created in the Sketchup program, based on the plans made available by the National Museum in Krakow, and then imported into the WUFI®plus program (Figure 1). Due to the size of the building, the complex layout of the rooms and the complexity of the construction of partitions, the model underwent some simplifications, which included unification of the thickness of partitions and simplification of their geometry (e.g. replacement of arches with straight lines). These simplifications were made so as not to change the parameters affecting the heat and moisture exchange through the partitions, i.e. the surfaces and the total mass of the partitions were preserved.

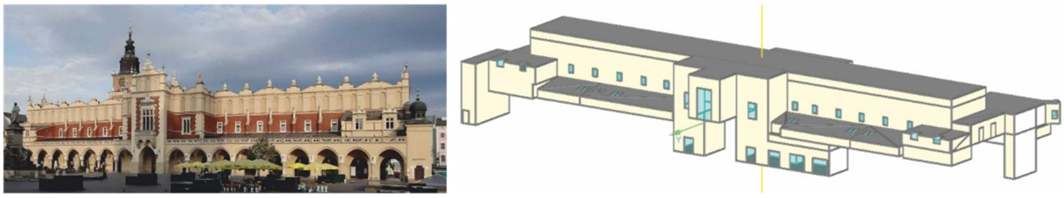

Figure 1. The Cloth Hall: western façade (a), WUFI®plus model (b)

The building's model covers all rooms belonging to the Gallery of Polish Art of the 19th century of the National Museum in Krakow. These rooms are divided, depending on the method of microclimate control, into nine calculation zones (exhibition rooms, heated rooms, a room for variable exhibitions and educational rooms, offices and storage rooms, a multimedia room, 3 air-conditioned zones and an attic). The main zone is the combined four exhibition rooms with a total area of 1 144 m^2 and a volume of 6 942 m^3. The remaining rooms of the building (such as restaurants, souvenir shops) are, so called, attached zones.

The basic construction material of the cloth hall is full brick. In the past it was usually used for building external and internal walls and vaults. The thickness of external walls in the modeled exhibition halls ranges from 0.7 to 1.0 meter. In the calculation model, the assumed value is 0.87 m. The floors of the exhibition halls are a combination of historical brick and modern reinforced concrete. The ceiling of the halls is made of steel structure covered with lighting panels. It separates the hall space from the attic of the cloth hall. The roof of the building is made of insulated partitions covered with copper sheets. The windows of the exhibition halls have been mostly walled with brick during one of the renovations; the remaining ones are made of wood equipped with a double, composite glazing units. The material data necessary for calculations, including historical bricks, was adopted from the WUFI®plus database.

3. Model validation

Parameters of the external climate (temperature, relative humidity, wind speed and direction, total and diffused solar radiation) were recorded on the roof of the Main Building of the National Museum in Krakow. The distance to the station from the object was approximately 1 km in a straight line. The use of an external climate measured at a certain distance from the object may lead to a slight error in the simulation calculations [9]. Based on the measured values (for 2015), a *.WAC file (WUFI ASCII CLIMAT) was created.

The parameters of the internal air were measured as part of the microclimate monitoring in the exhibition halls. Due to the fact that all exhibition rooms are interconnected (the doors between rooms are not closed), the average temperature and relative humidity of air were calculated based on the theory of mixing air streams due to the volume of individual rooms.

On the basis of ticket sales in 2015, the average hourly number of visitors was estimated (depending on the month). The adopted unit heat gains (by convection – 101 W and by radiation – 69 W) and moisture (98 $g \cdot h^{-1}$) correspond to the metabolic activity at the level of 1.6 met (adult standing person). For this activity, the unitary CO_2 emission is 59 $g \cdot h^{-1}$.

The calculations also include heat gains from lighting. Average hourly gains heat from the light is assumed to be 17 160 $W \cdot h^{-1}$ [10].

Exhibition halls are supported by four air handling units (Figure 2a). The air from the intake extends goes through the rotary heat exchanger, then: in the summer it is cooled and dried in the wet cooler, and then heated to the supply air temperature in the heater; in winter it is heated in the heater and then moistened with a steam generator (Figure 2b). The air cooler located before outlet is used for heat recovery for chillers.

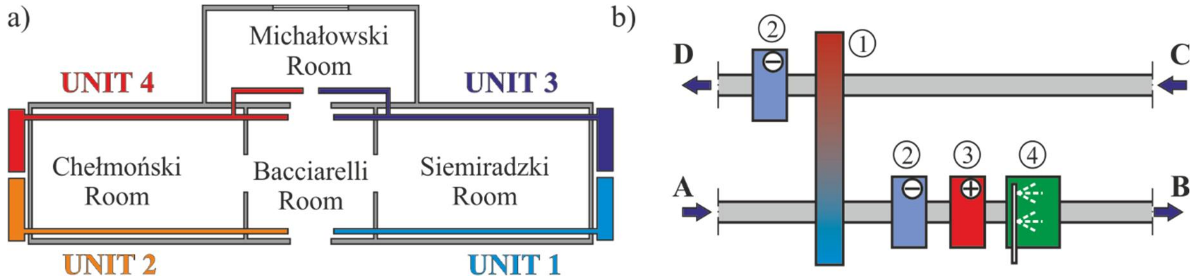

Figure 2. Separation of air from air-conditioning units to individual exhibition rooms (a) and operating diagram of air-conditioning units (b): A – intake air, B – supply air, C – exhaust air, D – outlet air; 1 – rotary heat exchanger, 2 – wet cooler, 3 – heater, 4 – steam generator

Both the temperature and relative humidity of the supply air to the exhibition rooms, as well as the airflow of individual air-conditioning units differ from each other. In the model, the exhibition halls constitute one zone serviced by one virtual unit. The averaged values of temperature and relative humidity of the air as well as the total efficiency of units were used for the calculations.

3.1 Microclimate parameters
Simulations were carried out assuming mentioned internal heat gains and supply air with averaged parameters. As a result of these simulations, annual variations in the temperature and relative humidity of the indoor air were obtained. These parameters are summarized by calculated averaged air parameters in exhibition halls.

Maximum absolute error for temperature is 3.7 K and mean one is 0.7 K. Errors below 1 K constitute, on a yearly basis, 72.7%. For relative humidity, the maximum error and mean are 13.2% and 2.8%, respectively. Errors below 5% constitute annually up to 85%. Over the year, the correlation, both for temperature and relative humidity, is significant – the correlation coefficient exceeds 0.6 (Spearman's test). It should be remembered that at each hour in a given month, the same number of visitors was established. The actual number of people for each hour of museum use is difficult to determine. As a result, there may be slight underestimates or overestimation of internal heat and moisture gains at individual times. This affects the course of parameter variability and, consequently, the value of the correlation coefficient. As shown in the monthly analysis from May to September, the correlation coefficients, both for temperature and relative humidity, exceed 0.8.

3.2 Energy consumption
To determine the accuracy of the calculation of energy consumption the differences in the enthalpy of external and supply air were calculated. Based on these difference, the hourly energy consumption for heating and cooling for air conditioning units serving the exhibition rooms was calculated. In 2015, air handling units delivered 663 990 kWh of energy for heating and 73 023 kWh of energy for cooling. It should be mentioned that these calculations do not include heat recovery.

The energy demands for individual air conditioning processes were calculated in WUFI®plus. In the calculations, as boundary conditions measured values of external and internal air parameters were assumed. Internal heat and humidity are also taken into account. According to simulation, the energy demand for space heating in 2015 amounted to 705 kWh. This value is 106% of the value calculated on the basis of the enthalpy difference in the air-handling unit. The Figure 3 shows the course of variation for energy consumption for heating based on the difference of enthalpy at the units and based on the simulation in the WUFI®plus program.

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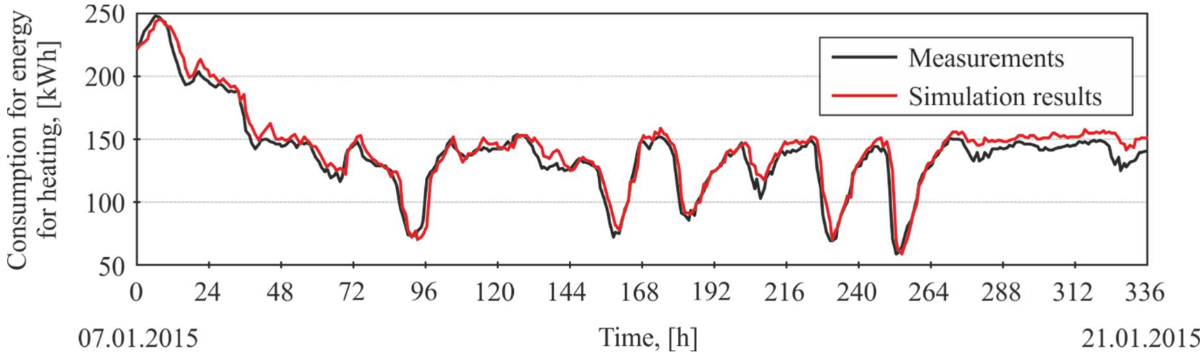

Figure 3. Comparison of calculated and actual heating energy consumption for the period 07 ÷ 21.01.2015

4. Theoretical calculation

To determine the impact of climate control scenarios on energy consumption in the calculations, three scenarios of full climate control including full air conditioning developed on the basis of ASHRAE, ICOM-IIC and MNK guidelines (Table 1), as well as scenarios considering only selected processes and their total absence have been included.

Table 1. Microclimate control option

	Temperature [°C]		Relative humidity [%]	
	Warm season	Cold season	Warm season	Cold season
MNK	18 ÷ 25	18 ÷ 21	40 ÷ 60	35 ÷ 55
ASHRAE AA	19 ÷ 23		42 ÷ 52[a]	
ICOM-CC - IIC	18 ÷ 25		40 ÷ 60	

[a] 47% is a long-term average from 2012 to 2016

At present, due to the lack of connection between the exhausting transfer grille and the exhaust duct, the air-conditioned zone (exhibition halls) is connected to the attic zone. The calculations additionally include variants assuming the separation of these zones by sealing the connection grille - exhaust duct. Calculations were carried out for two cases: with a fixed exchange rate equal to 3.0 h^{-1} (average airflow of air-conditioning units measured in 2015 related to the volume of exhibition halls) and with constant average airflow of units measured in 2015.

Air handling units serving exhibition halls work only on the outside air (due to the lack of space in the technical space it is impossible to install the air recirculation section). Hypothetically, however, it is possible to control ventilation due to the permissible concentration of CO_2 (the maximum permissible level of CO_2 concentration was assumed at 1 000 ppm; the minimum fresh air quantity for hygienic reasons is 20%).

The calculation was made taking into account heat recovery or its absence. Taking into account all assumptions resulted in the development of 29 variants of simulation.

4.1 Microclimate shaping

As a result of the calculations annual courses of variability of temperature and relative humidity of air in exhibition halls were obtained. To determine the "zero state", calculations were made assuming passive shaping of the microclimate, followed by heating, humidification and cooling with dehumidification.

If microclimate is shaped passively and with the air change rate (*ACR*) at 0.1 h^{-1}, annual fluctuations of temperature in the range 0.8 ÷ 28.4°C (with annual average 13.5°C) and relative humidity in the range

50.6 ÷ 91.7% (with annual average 76.5%) were obtained. With only infiltration, the CO_2 concentration exceeded the permissible value of 1 000 ppm. The maximum concentration was 1990 ppm and the average was 834 ppm. Based on the calculations, it was found that the *ACR* at which the concentration of CO_2 does not exceed 1000 ppm is 0.5 h^{-1}. The maximum concentration decreased to 882 ppm, and the average to 447 ppm. A change in *ACR* resulted in a change in the parameters of the indoor air. The minimum air temperature was -0.2°C, maximum 28.5°C, and the average 13.0°C. Relative humidity ranged from 37.8 ÷ 95.5% with an average of 69.6%.

To meet the requirements of the National Museum in Krakow it is necessary to introduce heating in the winter as well as year-round dehumidification of the air. Increasing the air temperature reduces its relative humidity, so in the next stage a simulation including heating was carried out. In the heating season, the minimum relative humidity decreased to 17.5%. The period in which relative humidity does not exceed 30% covers 927 hours, which is 10.6% of the year. In the summer, relative humidity still exceeds 60% (2138 hours, which is 24.4% per annum). In the summer there is little overheating (maximum temperature reached 28.6°C). The time of exceeding the recommended temperature of 25°C was 424 hours, which is 4.8% of the year. However, 45% of this period are exceeded only 1 K. According to the above analysis, to maintain even the least restrictive requirements, it is necessary to use full air conditioning.

4.2 Energy consumption

Given the current usage (compliance with the requirements of the National Museum in Krakow and the connection of exhibition halls with an attic, 85% heat recovery) as a result of the calculations annual energy demand for heating equal to 269 987 kWh were obtained. The maximum hourly energy demand amounted to 11 393 kW. The period in which heating was necessary comprised 5972 hours, which is 68% per annum. In general, the heating period covered the period from January to the end of March and from November to December. However, from April to June there were periods in which heating was required, a similar situation took place in September and October. In April there was a need for heating in almost 91% of the month, in May in 63%, in September in 80%. Cooling is required only in 8% per annum. The energy demand for this process is 11393 kWh. In order to dry the air to the desired level of relative humidity during the year, 226 522 kg of water should be drained out of it. The energy demand for dehumidification was therefore 430 391 kWh [11]. The period when dehumidification is required is 2 920 hours, which is 33% of the year. In order to maintain the minimum required humidity, it is necessary to bring to it, annually, 233 192 kg of water [11]. To evaporate this amount of water, it is necessary to bring 161 939 kW of energy. The period in which air humidification was required amounted to 4 106 hours, which is 47% of the year. Depending on the calculation variants, the share of energy demand for individual air treatment processes may differ from each other (Figure 4).

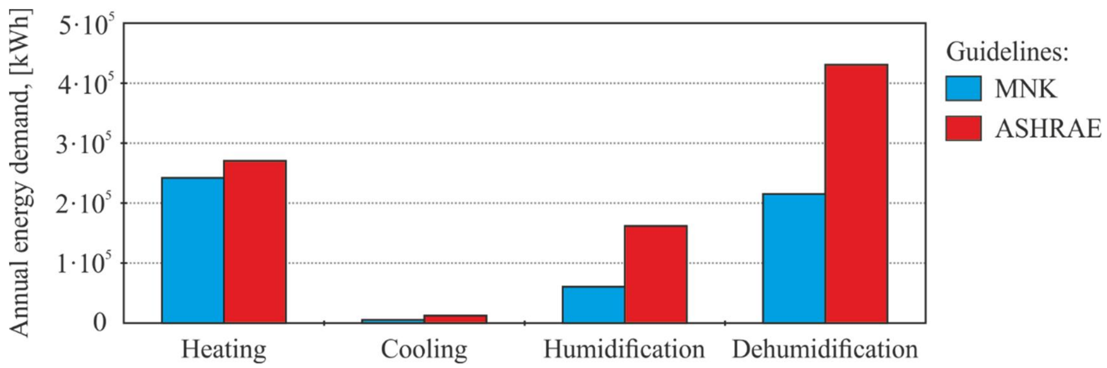

Figure 4. Annual energy consumption for individual processes for ASHRAE and the National Museum in Krakow (MNK) guidelines

Separation of the exhibition rooms from the attic results in a reduction of the heating energy demand, in the case of work only in fresh air by 22% and by 2% in the case of ventilation control based on the permissible CO_2 concentration. Introduction of ventilation control based on CO_2 concentration results in a significant reduction in the demand for heating by about 76%.

For variants assuming work only on outdoor air, separating the attic gives savings by an average of 20%. In the case of ventilation control based on CO_2 concentration, this separation results in an increase in cooling demand by up to 50%. The cooling demand decreases in case of change to ventilation control based on the CO_2 concentration (savings amounting to 80% in the case of a connection with an attic and 60% without this connection). The narrowing of the permissible variations of temperature and relative humidity of the air resulted in an approximate 59% increase in the energy demand for cooling.

The change of the requirements regarding the formation of the microclimate to the recommended by ICOM-CC and IIC resulted only in the increase of the energy demand for humidification (65% for calculations taking into account work only on fresh air and 140% for calculations with CO_2 concentration control) and slight reduction for dehumidification (about 9%). In the case of changes to the ASHRAE guidelines energy demand for heating increased by an average of 12%, for cooling of 185% and for humidification and dehumidification of 244% and 112%, respectively. In the case of variants in which CO_2 control was taken into account, almost 3.5 times more energy demand for humidification was induced.

To estimate the actual benefits or losses resulting from the change of use, all processes (heating, cooling, humidification, dehumidification) should be analysed all together. In the total energy demand, the energy demand for cooling was omitted. This is due to the fact that in the case of the Cloth Hall, air cooling is carried out together with dehumidification (in a wet cooler). By separating the exhibition rooms from the attic, a 15 ÷ 20% reduction in energy demand was obtained (depending on the ventilation capacity) – Figure 5. Controlling ventilation based on the permissible CO_2 concentration using air recirculation is of course the most economically advantageous variant. If such a solution was technically possible, 70% savings could be made for the Cloth Hall. The application of the ICOM-CC - IIC guidelines does not significantly increase the energy demand. The total increase in the amount of energy required in this case results from the higher relative humidity in the winter than in the MNK guidelines. In order to meet the requirements of ASHRAE, an increase of 65% of the energy demand should be expected.

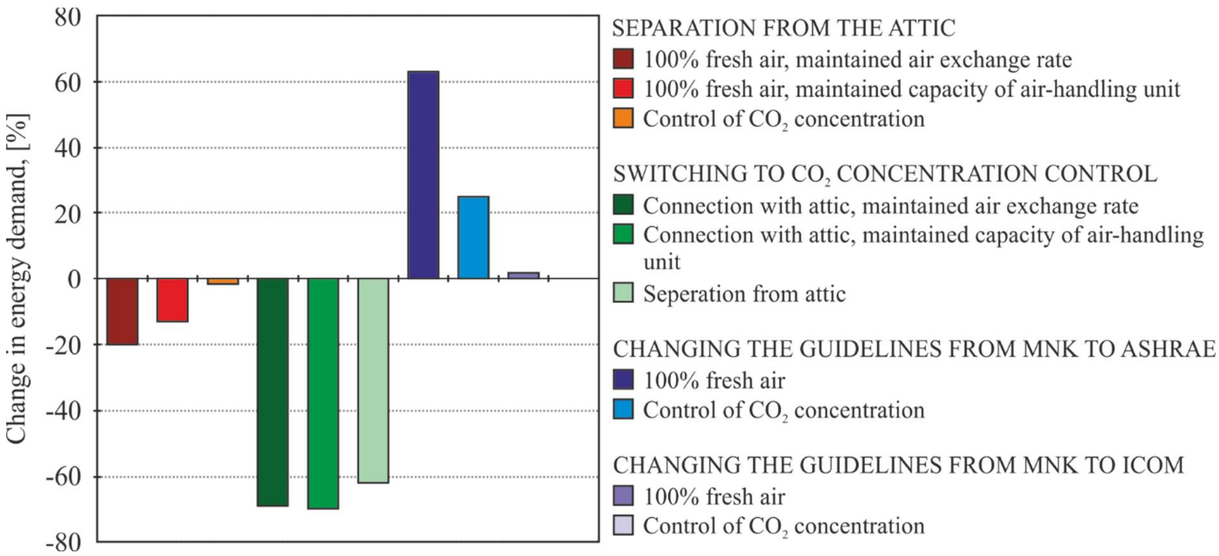

Figure 5. The average change in the total energy demand for air conditioning

5. Conclusions

Due to the specificity of historical building, reduction of the energy consumption to "0" is practically impossible. The construction of the building and the conservation requirements limit the thermal insulation of the partitions. Maintaining appropriate, for the museum collections, microclimatic conditions requires full air-conditioning (heating, cooling, humidifying, dehumidifying). As shown in the above analysis, savings should be sought in the correct technique of microclimate control, understanding of the technology used as well as the manner in which a given installation is designed, executed and operated. Where possible, museums that are housed in historical buildings should be treated as a case study. Wherever applicable, the requirements regarding the microclimate parameters should be relaxed to the highest extent possible.

6. Acknowledgments

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7. Literature

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