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A CFD-BASED METHOD FOR BIODETERIORATION PROCESS PREDICTION IN HISTORICAL LIBRARIES AND ARCHIVES

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Abstract— **This research provides a method, based on Computational Fluid Dynamics (CFD), that allows the prediction of damage-related and biodeterioration processes in materials and human health risks. The suggested method facilitates knowledge of the incidence and correlated effects of indoor air movement, air temperature and humidity distribution over time, in different air volume sub domains and on different surfaces (i.e. wooden shelving units and books, paper collections and incunabula) to fundamental parameters of microorganism growth, i.e. the water activity number and logarithmic growth rate. Comprehensive literature on biodeterioration and health problems associated with building moisture and biological agents was used as scientific evidence for the proposed methodological approach. CFD transient simulations applied to a real case study (the Palatina Libraryin Parma, Italy) suggested the most important means for predicting interior surfaces, building structures, zones and air volumes of persistent dampness and microbial growth adverse for human health prevention and cultural heritage conservation.**

Key words— **microclimate, indoor air quality, biodeterioration, cultural heritage, CFD**

I. INTRODUCTION

All Museums, historical buildings, archives and libraries, especially in regions with warm and humid climates, have a widespread problem concerning biodeterioration of organic materials due to bacteria and fungi colonization. The buildings very often suffer from water condensation phenomena due to poor ventilation, maintaining relevant microclimatic conditions for widespread development of microorganisms in cellulose artefacts (books, textiles, paintings, furniture, wood sculptures), proteinaceous objects (parchment, vellum, leather, mummy skin) and other materials. Microbial development poses two serious risks:metabolic production of organic substances and chemical reaction to various materials (e.g. pigments, enzymes, cellulases and proteases, organic and inorganic acids, chelating agents and other biochemical substances) and health risks for personnel and visitors due to detrimental microorganisms, released contaminants and toxins. It is well known that there are various methods for assessing indoor air quality based on active and passive air sampling, often combined with surface sampling techniques [1]. Microbiological and microclimatic indoor quality assessment are usually carried out as quantitative and qualitative evaluation of bacterial and fungal growth, supplemented by the study of biological contamination of interior surfaces with the use of cultivation methods [2].

Many investigations in libraries and archives have been carried out using optical and scanning electron microscopic techniques combined with agar plate cultures and DNA analysis [3]. Other studies have used non invasive methods based on sampling and water content evaluation, microclimatic measurements and molecular identification of the bacterial isolate with DNA, RNA and protein analysis [4]. Different non invasive techniques have been proposed, e.g. application of molecular biology techniques to cultural heritage environments showing that new spoiling taxa and unsuspected microbial consortia are involved in the discolouration and biodeterioration of books and paper- supported works of art. Moreover, the investigation by means of enzymatic and microscopy techniques of the interaction between the microbial flora, responsible for damage, and the organic and inorganic structural elements in paper proved to be fundamental, in order to understand complex phenomena involved in the alteration of materials of cultural value.

Another example is Scanning Electron Microscopy (SEM) that is an invaluable tool allowing the direct observation of samples and providing knowledge of the association of specific microorganisms with types of biodeterioration. The SEM technique is also highly informative in the evaluation of the effects of curative treatments directly on materials and organisms, thus it represents a micro-invasive methodology or, when concerning the sample, a non-destructive technique [5]. Other authors suggest a molecular fingerprint method as an effective analytical tool for the monitoring of indoor air quality, highlighting the stability of bacterial airborne diversity and defining a molecular signature of indoor air bacterial content [6].

Most of the literature on this subject demonstrated that conventional control of temperature and relative humidity in conformity with standards is insufficient to prevent material colonization, mould contamination and growth on paper material, in particular bindings made of leather, parchment or cotton fibres, especially if enclosed systems with low ventilation rates are used. It has been proved that even when a chemically cleansed collection of paper and/or parchment documents, have only sporadic contact with people (technicians and/or visitors) but are influenced by ambient air, it can undergo microbial contamination again and become an important emission source [7]. A recent study developed and laboratory-tested a novel Fungal Spore Source Strength Tester (FSSST): this approach provides data that allows assessing the strength of mould sources in homes with respect to their maximum ability to contaminate indoor air with fungi [8].

This study and also other important research on this subject, have highlighted the fact that fungal growth mainly depends on the nutrient availability, alkalinity, porosity, and water activity of the material. Water activity is defined as the

amount of free water in the material available for microbial growth and depends on the moisture absorbing potential of the growth material [9; 10; 11].

The knowledge of variation of microclimatic and microbiological ambient conditions, the effect of mechanical isolation from the inflow of outdoor contaminants (e.g., an augmentation to air-tightness of the room, air-conditioning system introduction, air flows and air pressure schemes control and regulation, etc.), microclimate parameter control, analysis of complex chemical structures of different materials, may solve, or at least decrease, the biodegradation risk of the stored collection maintaining indoor air quality and proper indoor hygiene requirements that are also fundamental for human health. Few studies in the literature have been carried out using the CFD (Computational Fluid Dynamic) technique for assessing the interaction between the indoor microclimate, (i.e. the result of interaction of building thermo-physics with outdoor environment such as external temperature fluctuations and solar radiation impulsive effects) and airborne microbial and microorganisms growth or death.

Some authors have used CFD modelling combining the indoor climate conditions and hygroscopic and mechanical behaviour of wood in the cabinet doors studied to predict damage risk potential of indoor climate variations concerrning the doors [12]. Research by the present authors has shown that CFD simulation of the indoor air flow and displacement mainly due to natural convection and buoyancy effects combined with moisture transport phenomena and people movements (also connected to sensible and latent heat released to the indoor ambient) provides crucial knowledge of the allowed microclimatic parameter bandwidth for the preventive conservation and maintenance of rare books and manuscripts, paper and all those materials, whose stability and conservation conditions are particularly connected with thermo-hygrometric parameter variation.

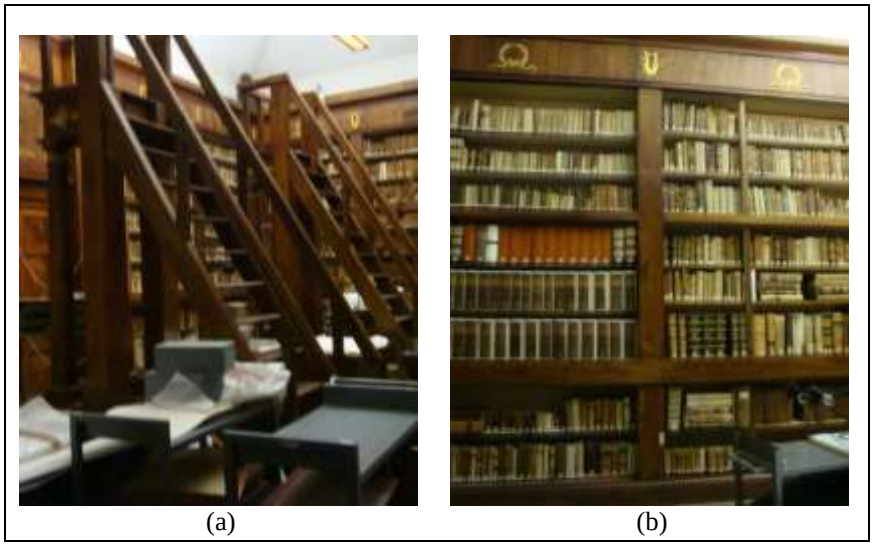
The CFD simulation approach, suggested by the authors, based on coupled heat and moisture transport, is a useful tool for investigating the stability requirements of microclimatic conditions, that play a key role in deterioration processes [13].

Our present study provides a useful model, developed by Computational Fluid Dynamics (CFD) with the multi-physic Finite Elements Method (FEM) approach, that allows the prediction of damage-related and biodeterioration processes in materials, risk for conservation and maintenance of paper materials and also health risks for persons. The knowledge of indoor air movement and air temperature and humidity distribution over time, in different air volume sub domains and different surfaces (i.e. wooden shelving units and books, paper collections and incunabula) were connected to fundamental parameters of microorganism growth, i.e. the water activity number and logarithmic growth rate.

II. MATERIALS AND METHOD

In indoor environments like libraries, museums and archives, the biological component of air (bioaerosol) may be a potential risk for the cultural heritage and for the health and safety of operators and visitors. The storage of books and archival materials inside historic buildings holding them has created unique environments for cellulolytic fungal and microbial species to inhabit. Biodeterioration of the cultural heritage is a crucial and complex question. Due to restrictions on personnel access, reduction in the number of visitors, and absence of activities which could influence indoor pollutant concentrations, means that the historic Palatina Library in Parma and in particular the Derossiana Room was the suitable studied environment. Physical, biological and microclimatic parameters of the environment have been collected during monitoring campaigns and discussed in [14].

The Derossiana Room is 6.90 m wide, 12 m long with a total volume of 496.8 m^3 (Fig.1). The room has two internal partition walls and two walls facing the external ambient. The smaller of these external walls, with an area of 48.28 m^2, has a central window with an area of 3.5 m^2 and is South-West oriented, the wider external wall is 42.20 m^2 and South-East oriented. It has a cross-vaulted ceiling. The geometry of the studied room is outlined in Fig. 2. In particular, two persons, the first standing and the second sitting, were considered and modelled. Fig.2 shows the exterior walls and partitions to other indoor environments (in yellow), the volume of air inside the room (in cyan) shaped at the top under the vault of the ceiling, the main furniture in the central part of the room (desk and stairs, in grey) and the two occupants (in magenta). Fig.3 shows all the other considered details of the room used in the numerical modelling: the wooden shelving perimeter (in mustard) containing books (light grey), the window (in blue), the lighting body shaped aluminum linear (dark grey) and the lamp (yellow). The total air volume in the room was modelled as a set of multiple sub-domains (Fig.4) in order to calculate the average values of the studied parameters in different portions of the ambient: i.e., the central portion of the air volume (CA) up to 4 m height from the floor is considered divided from the zone of the vaulted ceiling (VR, which extends over the whole volume of air, from 4m height from the floor to the top of the vault, then 6.5 m height above the floor), the air volumes next to the peripheral zones of shelving and books (BK) and the air volume close to the window (WN) and door (DR).



(a) (b)

Fig. 1. Derossiana Room images

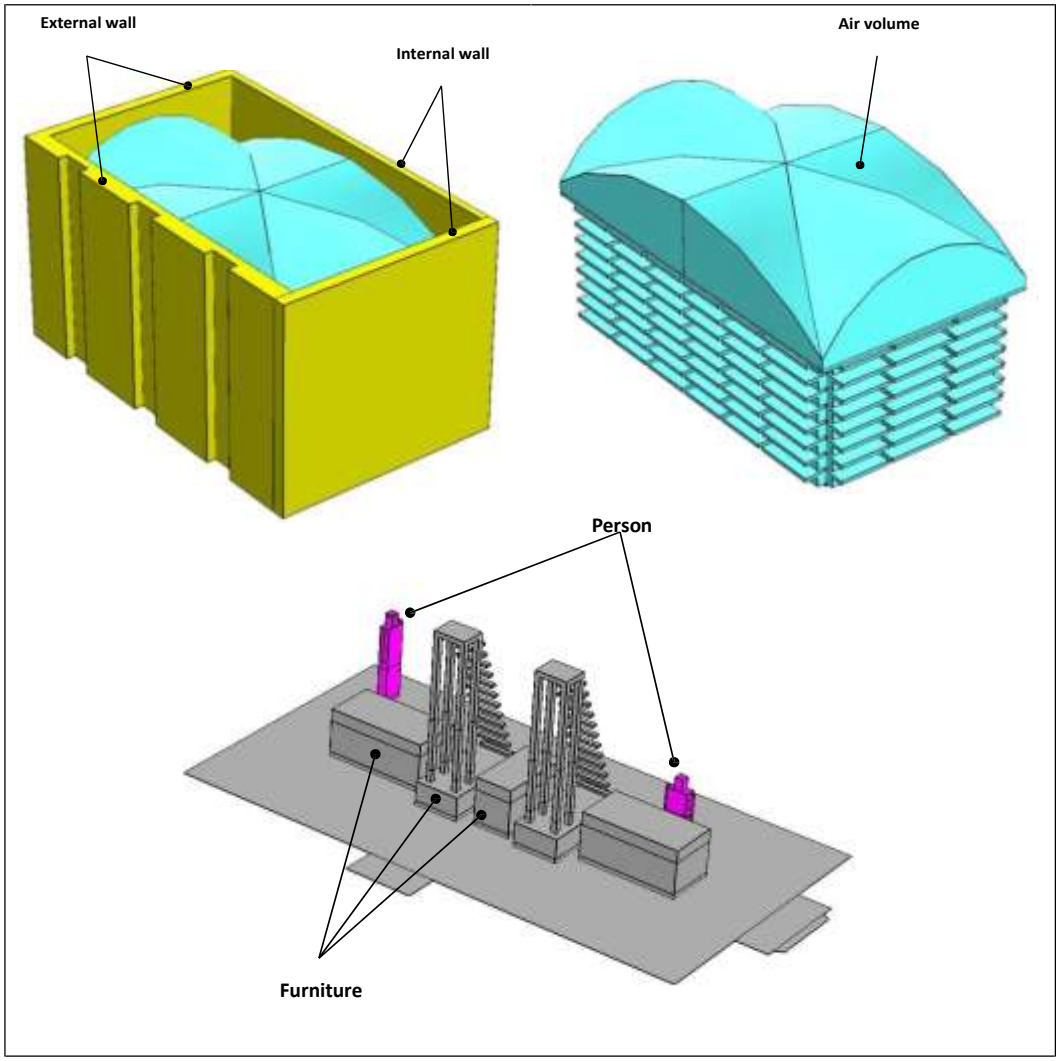


Fig. 2. Numerical model geometry with walls (yellow), air volume (cyan), main furniture in the centre of the room (gray) and people (magenta).

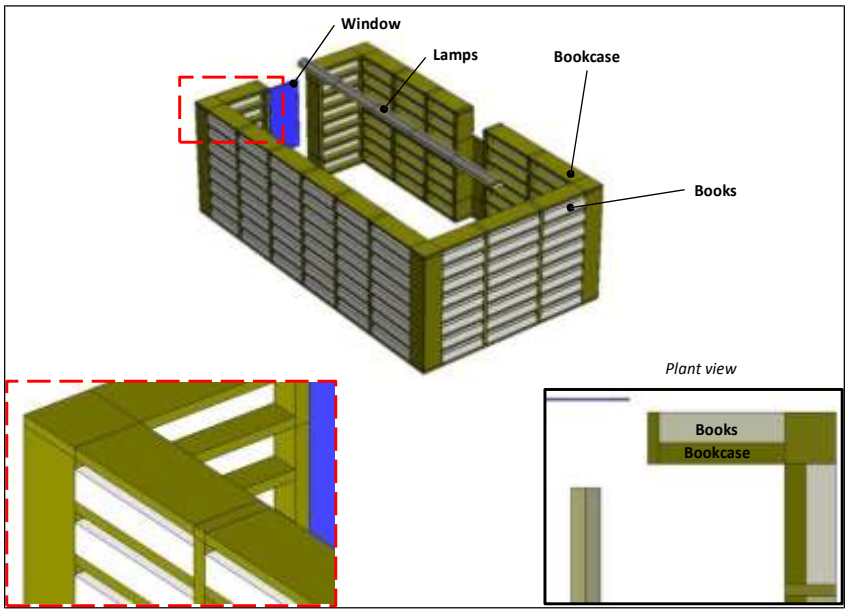


Fig. 3. Numerical model geometry with the wooden shelving perimeter (in mustard) containing books (light gray), the window (in blue), the lighting body shaped aluminum linear (dark gray) and the lamp (yellow)

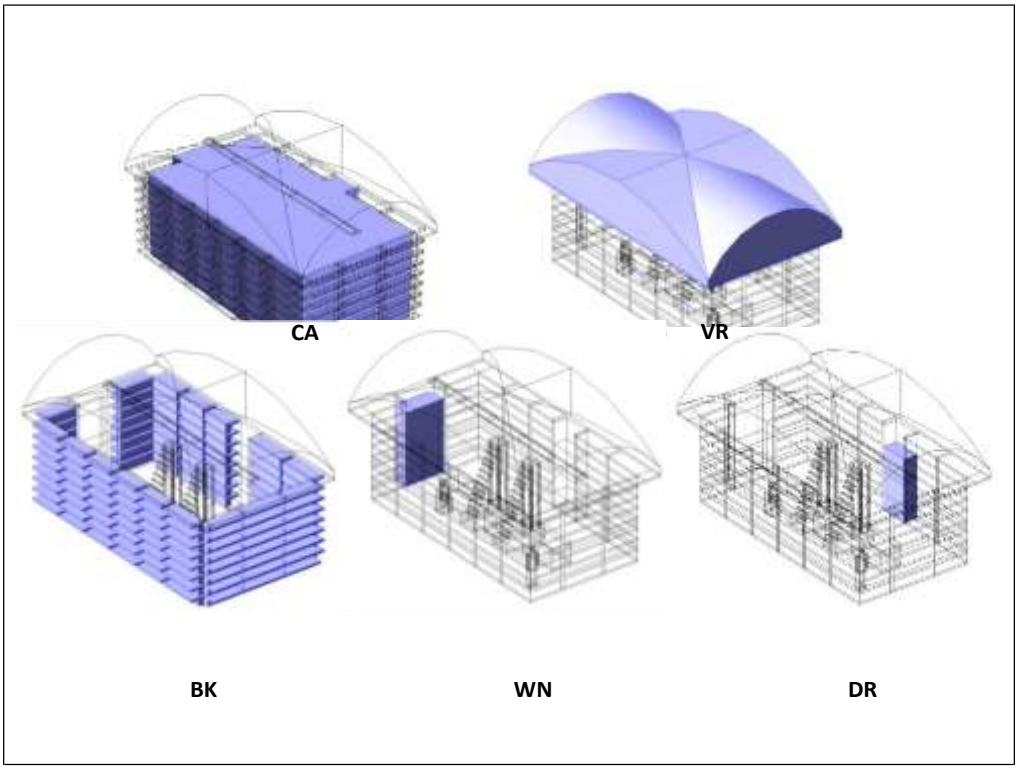


Fig. 4. Air volume division and its labels: central portion of the air volume (CA), volume of the vaulted ceiling (VR), air volumes next to the peripheral zones of shelving and books (BK) and the air volume close to the window (WN) and door (DR)

In order to compute the transient internal air flows, the Reynolds Averaged Navier-Stokes equations were numerically solved adopting a RANS scheme assuming the air as Newtonian fluid and uncompressible flow. Momentum equations were coupled with a standard k-□□closure scheme [15] in order to model turbulence by an eddy viscosity approach. Resolution of Navier-Stokes equations of continuity and momentum conservation, can be written as follows:

$$\rho\frac{\partial \mathbf{U}}{\partial t} + \rho\left(\mathbf{U}\cdot\nabla\right)\mathbf{U} = -\nabla\cdot\left[-p\mathbf{I} + \left(\eta+\eta_T\right)\left(\nabla\mathbf{U} + \left(\nabla\mathbf{U}\right)^{\mathrm{T}}\right)\right] + F \quad (1)$$

$$\nabla\cdot\mathbf{U} = 0 \quad (2)$$

$$\rho\frac{\partial k}{\partial t} + \rho\mathbf{U}\cdot\nabla k = -\nabla\cdot\left[\left(\eta + \frac{\eta_T}{\sigma_k}\right)\nabla k\right] + \frac{1}{2}\eta_T\left[\nabla\mathbf{U} + \left(\nabla\mathbf{U}\right)^{\mathrm{T}}\right]^2 - \rho\varepsilon \quad (3)$$

$$\rho\frac{\partial \varepsilon}{\partial t} + \rho\mathbf{U}\cdot\nabla\varepsilon = -\nabla\cdot\left[\left(\eta + \frac{\eta_T}{\sigma_\varepsilon}\right)\nabla\varepsilon\right] + \frac{1}{2}C_{\varepsilon 1}\frac{\varepsilon}{k}\eta_T\left[\nabla\mathbf{U} + \left(\nabla\mathbf{U}\right)^{\mathrm{T}}\right]^2 - \rho C_{\varepsilon 2}\frac{\varepsilon^2}{k} \quad (4)$$

$$\rho C_p\frac{\partial T}{\partial t} + \rho C_p\mathbf{U}\cdot\nabla T = \nabla\cdot\left(\lambda\nabla T\right) + Q \quad (5)$$

°C, the maximum of all the hourly temperature values is 37.7

°C and the minimum is -5 °C. Therefore, the typical day, representative of the worst summer conditions with the maximum air temperature value (22 July), and the typical day, representative of the worst winter condition, the one with the minimum temperature value (20 January), were selected.

On the basis of trends, preliminarily calculated, expressing the time evolution of the solar-air temperature (T_ext) , that is a correction of the external air temperature taking into account the solar radiative flux and the infrared exchanges from the sky [13], and relative humidity (RH_ext), all the basic boundary conditions applied to solve governing equations during those transient simulations of interest.The presence of lamps (5 linear modules, each one of power 50W), people presence (daily occupancy schedule: from 10.00 to 12.00 and from 16.00 to 18.00) and thermo-hygrometric conditions of the conditioned and adjacent rooms to the one studied. For these adjacent rooms, transient conditions due to the regulating system of the present air conditioning plant, were implemented taking into account the control of two (winter) and three (summer) different levels of the set-point temperature (T_int), while for relative humidity a constant value equal to 50% was considered. Figs. 5a-c and 6a-c, show, respectively for the winter and summer typical days, the time trends of boundary conditions and source terms of sensible heat (Q_S) and vapour flux (G_{vap}) released by each person, during a 12 day period, in which the source term is the thermal buoyancy force. The energy equation for air temperature field solution can be expressed by:

where the source term refers both to the metabolic heat released by people inside the room and total heat dissipated by the lighting system. The numerical model used for solving coupled heat and moisture transfer phenomena, is based on the relative humidity procedure while the moisture potential adopting an Euler-Euler scheme to model transport and diffusion of moisture in the air [16]. Its validation with experimental data, obtained from the on-site monitoring campaign, with good agreement, is provided in our recent paper [13]. In the present work, we used this model for transient simulations of coupled heat and moisture transfer, in relation to indoor and outdoor climate variations, solar radiation conditions, the air flow distributions inside the room and people presence.

The partial differential equation considered for solving the relative humidity (RH) fields reads as follows:

$$\frac{\partial RH}{\partial t} + \mathbf{U}\cdot\nabla RH = \nabla\cdot\left(D_p\nabla p_{sat}\right) \quad (6)$$

Thermo-physical properties of different materials used for transient simulation are provided in Tab.1.

Reference climatic conditions used for the analysis correspond to the "typical days", whose climate hourly data were processed according to the UNI EN ISO 15927-4 [17] for Parma (Italy). Analyzing all the climatic data of the standard year of Parma, the average annual air temperature value is 14.5 taken as a reference for the analysis in order to obtain a simulation result, of each typical day, independent of the initial conditions of the model. In order to get a periodic regime (that is easy to reach by choosing "consistent" initial conditions), stabilized over a not too long time period, all the calculations were initialized using, as initial distribution of dependent variables, the solution of the same model at stationary conditions obtained assuming constant values for all the time- dependent boundary conditions, and corresponding to the their value assumed at the initial time of transient simulations. The main purpose of our research concerns the investigation of the incidence of indoor thermohygrometric variations on microbiological deterioration process of different materials. Two parameters for the control of microorganisms (mainly bacteria and fungi) growth and proliferation, and strictly connected to microclimatic parameters, were evaluated and monitored starting from transient simulation results. The first parameter, widely used in the food industry, known in the literature as "water activity number" a_W is the partial vapour pressure of water in a substance divided by the standard state partial vapour pressure of water. In the food science field, the standard state is most often defined as the partial vapor pressure of pure water at the same temperature, then pure distilled water has a water activity equal to one. The parameter is analytically expressed as follows:

$$a_W = \frac{p}{p_0} \quad (7)$$

where p and p_0 are respectively the value of pressure and saturation pressure of water at the same temperature. Therefore the a_w value is always between 0 (substance without water content) and 1 (water). At equilibrium state, in the air of the environment, the parameter a_W definition corresponds to relative humidity (RH). Then we referred to this last definition whose equation was implemented in the simulation model.

Table II. Thermophysical Properties of Different Materials and Those Attributed To Persons

Material	□	□	k	C_p	□	□□$_p$	D_w
	[kg/m^3	[Pa	[W/(m	J/(kg	[kg/m	[kg/(m s	[m^2/s
Wall	1600	-	0.47	840	0.0068	3.1E-11	4.2E-
Glass	2500	-	1.00	800	0	0	0
Wood	500	-	0.50	1000	0.086	4.5E-11	6.1E-
Paper	940	-	0.12	1340	0.097	2.3E-11	3.1E-
Person	950	-	0.62	4180	-	-	-
Aluminiu	2700	-	160	900	0	0	0
Air	p □RT □	5E-5	0.04	1004	0.028	1.9E-10	2.5E-

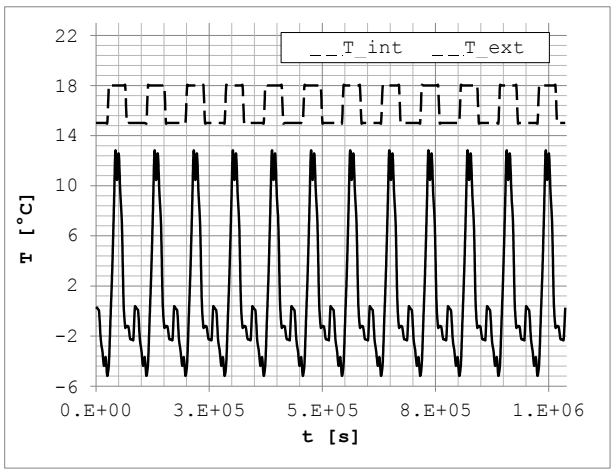
Table III. Mean Temperature (Tm) And Growth Rates For Different Bacteria Thermal Characteristics (G□10; G□20; Gμ□30) Calculated In The Typical Summer Day During Two Times (H 12.00 And H 22.00) For Different Sub-Domains (Ca, Vr, Bk, Wn, Dr) And Surfaces (S1, S2, S3)

		Summer day - Time 12.00				Summer day - Time 22.00			
		Tm	**G□10**	**G□ □**	**G□ □**	**Tm**	**G□10**	**G□ □**	**G□ □**
		[°C]	[-]	[-]	[-]	[°C]	[-]	[-]	[-]
Air volume	CA	35.1	6.2%	12.5%	18.7%	31.8	6.9%	13.8%	20.6%
	VR	40.2	5.4%	10.9%	16.3%	36.5	6.0%	12.0%	18.0%
	BK	33.9	6.4%	12.9%	19.3%	30.2	7.2%	14.5%	21.7%
	WN	42.7	5.1%	10.2%	15.4%	31.8	6.9%	13.7%	20.6%
	DR	27.5	7.9%	15.9%	23.8%	29.4	7.4%	14.9%	22.3%
Shelf A	S1	26.6	8.2%	16.4%	24.6%	29.3	7.5%	14.9%	22.4%
	S2	25.5	8.6%	17.2%	25.7%	28.5	7.7%	15.3%	23.0%
	S3	24.3	9.0%	18.0%	27.0%	27.7	7.9%	15.8%	23.7%
Shelf B	S1	42.0	5.2%	10.4%	15.6%	31.1	7.0%	14.0%	21.1%
	S2	42.3	5.2%	10.3%	15.5%	31.2	7.0%	14.0%	21.0%
	S3	42.6	5.1%	10.3%	15.4%	31.2	7.0%	14.0%	21.0%

It is well known that there are several hundred different microbial species responsible for library stock biodeterioration. Among them, there are fungi and bacteria with cellulolytic, proteolytic and lipolytic properties. We considered the large amount of research in the literature on microbial contamination, microorganism growth and biodeterioration that have demonstrated that fungi are particularly dangerous because they have considerable tolerance to environmental conditions [18;19;20;21]. They require very different relative humidity values than bacteria for their development and produce spores that are easily dispersed by moving air. Spore dispersion is the main cause of contamination in the environment and of hazards for human health [22]. These species of bacteria and fungi, in particular filamentous fungi (mould), grow indoors when sufficient moisture is available. Taking into account the above literature evidence it was possible to define the optimal conditions of growth for different fungi species. Generally, these conditions correspond to a_w value between 0.7 and 1, and the optimum temperature ranges for reproduction are strongly dependent and variable with the different characteristics of different species. In particular, the optimal conditions for cellulolytic fungal and microbial species growth and development, were associated with cellulose that is the most organic compound, and not with the different nature of paper material. The second parameter used for monitoring and analyzing the interaction between microclimatic conditions and the potential growth of microorganisms is defined as the logarithmic growth rate [23; 24]. It is expressed according to the expression:

$$G = \mu \left(\frac{1}{293} - \frac{1}{T} \right) \cdot \frac{1}{2.303 \cdot R} \quad (8)$$

where G is the log growth rate, μ is the temperature characteristic (different for particular microbe) that is a constant value by bacteria/fungi type and expressed in kcal/mol, R ideal gas constant and T temperature in Kelvin.



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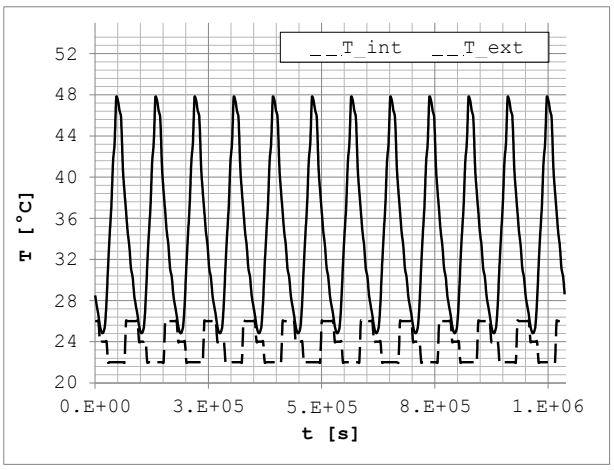

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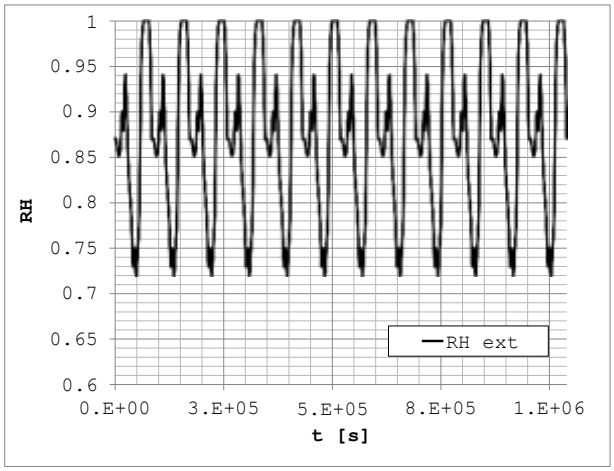

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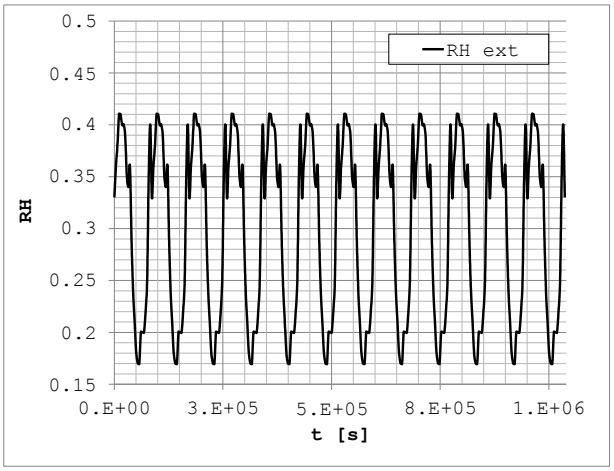

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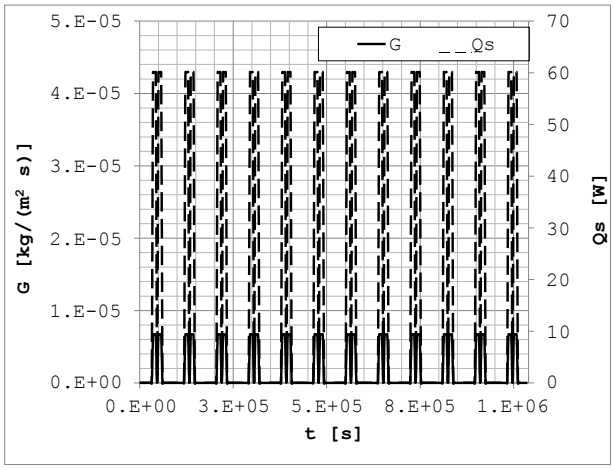

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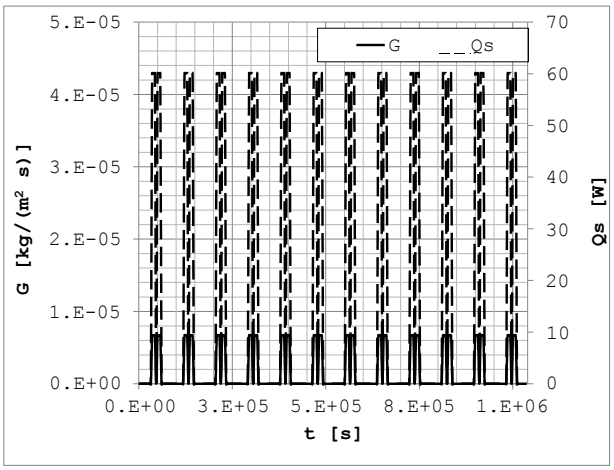
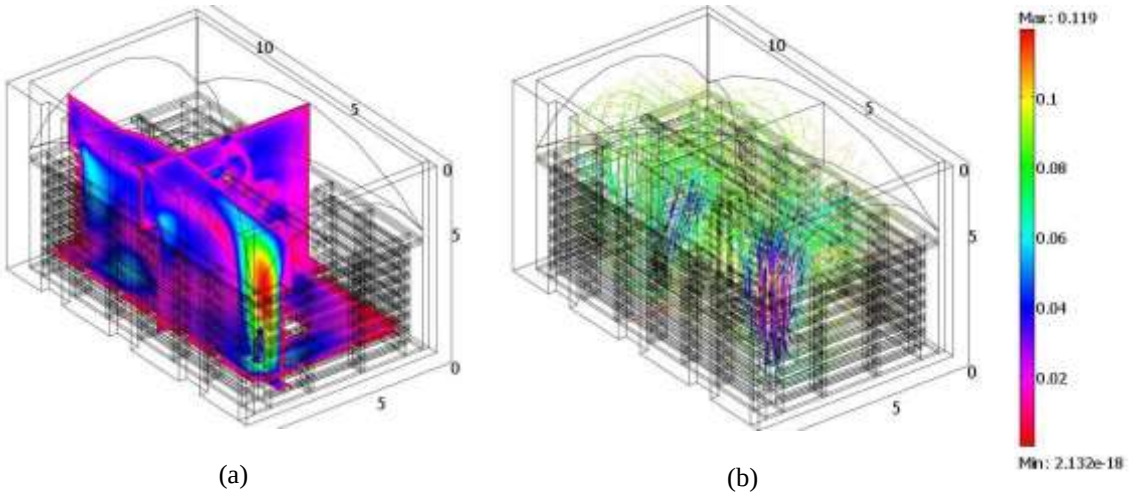


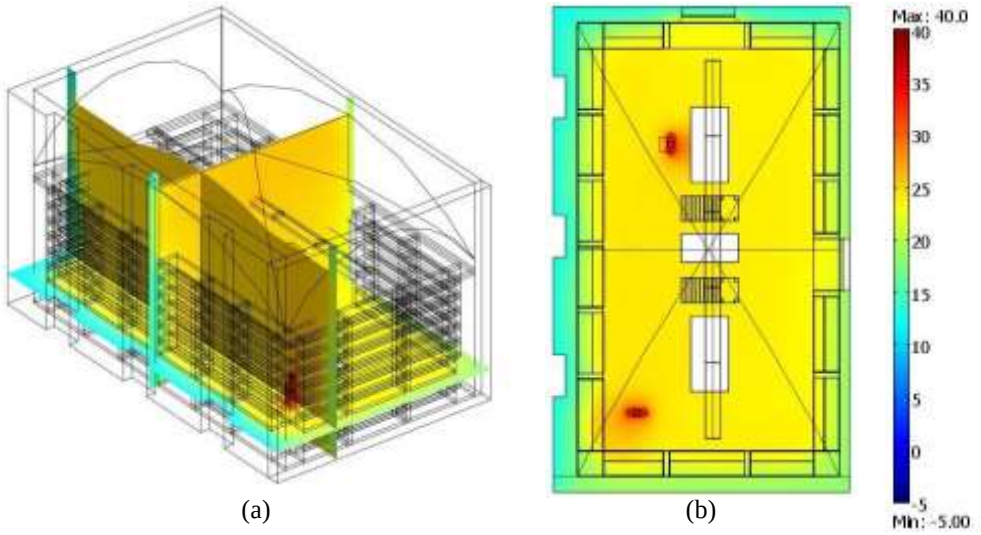
(f)

Fig. 5. Temporal trends of external climatic conditions, the environmental conditions in local and neighbouring thermohygrometric internal sources due to people presence – winter (left: a,b,c) – summer (right: d,e,f)



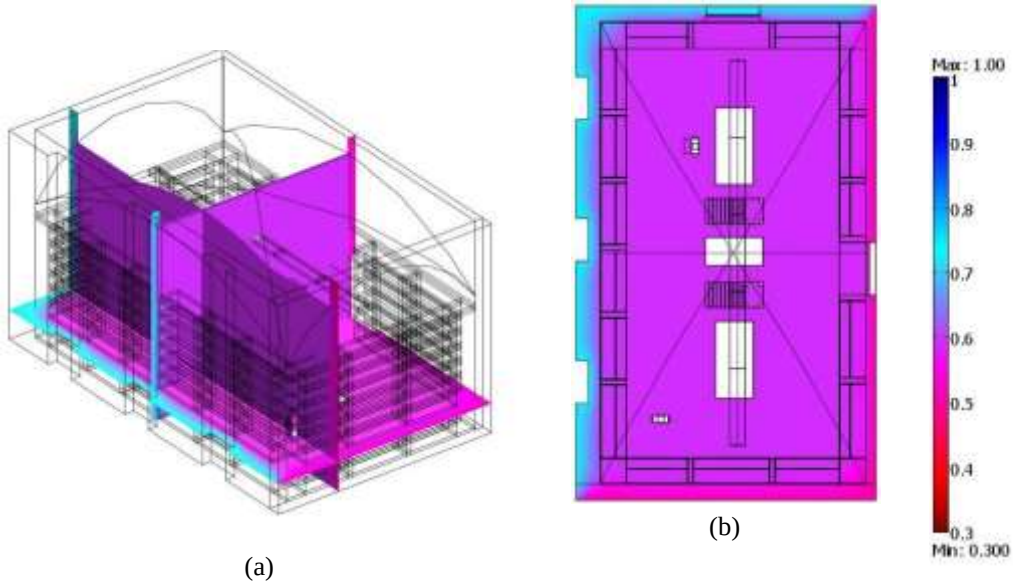
(a) (b)

Fig. 6. Air flow field on 3 section planes (a) and streamlines on the volume (b) in winter conditions (12 December, h 12.00)



(a) (b)

Fig. 7. Thermal map on 3 section planes (a) and top view from horizontal plane (b) in winter conditions (12 December, h 12.00)



(b)

(a)

Fig. 8. Relative humidity distribution on 3 section planes (a) and top view from horizontal plane (b) in winter conditions (12 December, h 12.00)

The relationship shown in eq (8), in analogy with the Arrhenius law from which it is derived, is adopted to describe for a given temperature range, the exponential trend of the microorganism growth rate with the same temperature [25].

This trend, expressed by a logarithmic scale, provides a linear correlation between parameter G and the local temperature. However, when temperatures approach the maxima for a specific microorganism, the growth rate declines more rapidly than when temperatures approach the minima for that same microorganism. Temperature characteristics have generally been given by the units kcal/mol. However, SI guidelines require the use of the Joule, and the meaning of the molar dimension in connection with bacterial growth is obscure. Hence, we calculated the Arrhenius constant in kcal/mol without expressing the units, in agreement with the suggested original description of μ [25;26].

III. RESULTS AND DISCUSSION

In the present section the main results obtained by transient simulation for the air flow and velocity fields, temperature and relative humidity distribution, are presented and discussed.

Fig.6 shows the air flow field due to natural convection, carried out from typical winter day simulation at h 12.00.

In order to evaluate the effect of the buoyancy driven airflow inside the ambient, we assumed that any imposed pressure gradient acts on air filling the numerical domain. This as reference. Referring to results carried out by transient simulations, the possibility and efficacy of correlations between building thermophysical performance, indoor microclimatic conditions, and risk factors for conservation and preventive protection of cultural heritage were evaluated, in relation to the potential growth of these microorganisms causing material biodeterioration.

For this purpose, an "index" of danger, due to different fungal species proliferation and development was defined. This index is Boolean, and its value 1 is given by the combination of humidity and temperature conditions compatible with microorganism (bacteria and/or fungi) potential growth. The humidity conditions are related to high rates of relative humidity, or water activity number for materials potentially at risk. The considered a_W range variation was defined as $0.7 < a_W < 1$.

Some different classes of temperature ranges, were associated with the a_w range variation, so that a group of indices was deduced, which hereinafter will be indicated by the symbol $I_{T1, T2}$, where subscripts T1 and T2 mean respectively the minimum and maximum temperatures of the reference temperature range. Analytically the Boolean value of the proposed index was defined as follows:

IF $T1 \le T \le T2$ AND $0.7 \le a_W \le 1$ THEN $I_{T1,T2} = 1$ ELSE $I_{T1,T2} = 0$ (9)

By way of an example of the proposed method, Figs.10a-d show on a plane of the horizontal section of the room (z = 1.5 condition reflects the real state of the room that is not equipped with a ventilation or air conditioning system. m above the floor) the value of the index $I_{-5,0}$, $I_{0,5}$, $I_{5,10}$, $I_{10,15}$.

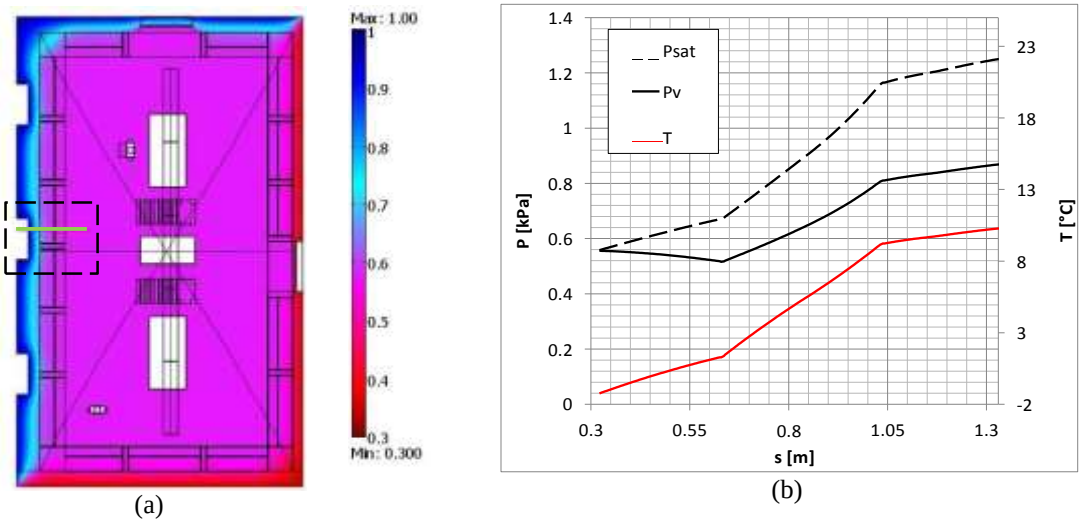
The flow fields show the effects of buoyancy induced by thermal heat sources inside the volume (people and lighting system). One may also note two macro-structures of internal recirculation defined by horizontal axis transverse and longitudinal due to the temperature difference between the two walls facing outside and the other two facing neighboring heated rooms. Fig.s 7a-b and 8a-b show, respectively, examples of thermal maps and distribution of relative humidity at the same time of the simulation. In order to assess mould risk and interstitial condensation inside the walls, the book shelving, and paper material blocks, the Glaser method designed for calculating the amount of interstitial condensate during a cold winter period and the theoretical amount of evaporable water in a cold summer, was used. The condensation check was performed, for the worst conditions (20 January at h 12.00) calculating and comparing the vapour partial pressure with the saturation pressure at the local temperature along an orthogonal line to the external wall.

In order to obtain appropriate condensation evaluation, results of transient simulation of heat and moisture transfer, taking into account boundary conditions (indoor and outdoor climate, surface transfer), initial conditions (construction moisture), definition of relevant hygrothermal properties referring to literature data, accuracy of numerical solution (test grid, grid space and time steps), were analyzed and compared.

Fig. 9a-b provides the relative humidity distribution and comparison between pressure trend on the section plane, taken Results provided by the above figures refer to a specifictime of solution (20 January, h 22.00). It should be noticed that in some zones, both in correspondence of the external walls, and of the wooden book shelving, and paper blocks representative of the heritage library collections, the value of the proposed index is 1 (red colour). Considering the interaction between outdoor and indoor climate, thermophysical behaviour of building structures related to their mass and specific heat of different materials, thermal capacity and inertia, it appears possible to identify which zones inside the room can be "affected" by a particular microclimate favourable to the growth of fungal microorganisms that can be the potential cause of deterioration of the stored library collections and risk for conservation and protection of the cultural heritage.

As a matter of fact, the specific humidity of the external air is always lower than that inside the ambient which has microclimatic features below the saturation condition; in correspondence with the minimum external air temperature value of -5.2°C and specific humidity of 2.39 g_{vapour}/kg_{air} in the internal ambient the mean air temperature value is 11.2 °C with a specific humidity of 5.49 g_{vapour}/kg_{air}.

Transient simulations for the summer period, during the typical day (22 July), highlighted the fundamental conditions to provide a value equal to 1 for the index $I_{T1,T2}$, that allows assessment and monitoring of the potential fungi proliferation.



(a) (b)

Fig. 9. Relative humidity distribution on the horizontal plane (a) with an indication of the chosen plane for the trends of vapour partial pressure (P_V), saturation pressure (P_{SAT}) and air temperature, shown in the graph to the right (b)

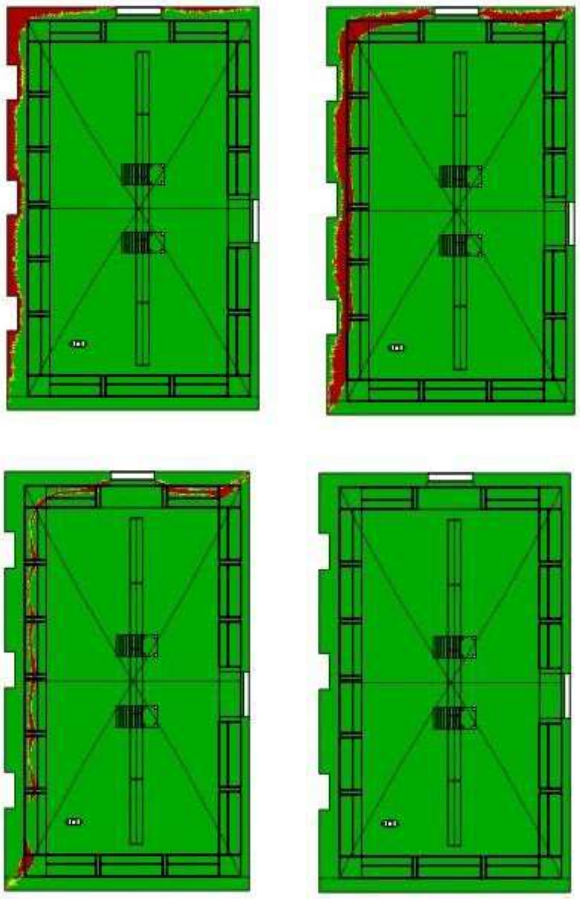


Fig. 10. Index $I_{T1,T2}$ value (red=1) e 0 (green=0) for $I_{-5,0}$ (a), $I_{0,5}$ (b), $I_{5,10}$ (c), $I_{10,15}$ (d) on the horizontal plane at 1.5 m from the floor at one time instant (12 December, h 22.00) – typical winter day simulation.

This fact happens in relation to a maximum value of the relative humidity of the external ambient of 40%, that is a value considerably outside the chosen referring range for the water activity number. Simulation results during the summer period pointed out that a combination between external climatic conditions, high thermal inertia and heat capacity of the building, and the small size of moisture and vapour mass transport, is not significant for the phenomenon of fungi and bacteria proliferation. As a matter of fact, the specific humidity of the external air is always lower than that inside the ambient which has microclimatic features below the saturation condition; in correspondence with the maximum external air temperature value of 37.7°C, the solar radiation is 645 W/m^2 and specific humidity 6.8 g_{vapor}/kg_{air} in the internal ambient the mean air temperature value is 32.2 °C and the specific humidity 13.02 g_{vapor}/kg_{air}.

Lacking real information and data on the logarithmic growth rate of fungi in the room, we referred to the small amount of published research on this subject [25; 26;27;28] to define the temperature characteristics, representing the activation energy, expressed by temperature ranges, and then to investigate the relationship between maximum bacteria growth rates and the correlated temperature characteristics. Therefore, starting from simulation results about transient microclimate conditions in the room, the logarithmic growth rate of these bacterial microorganisms co-responsible for deterioration processes of the library book collection but also potentially harmful to health of occupants was evaluated. This analysis was performed by applying eq.(8) in relation to the average temperature obtained in the different sub-domains (both for solid volumes of wooden shelving or paper blocks BK, and the air volumes i.e. CA, VR, WN and DR as defined in the implementation phase). The logarithmic growth rate was calculated for assigned values of the parameter μ, corresponding to a given particular species. Analyzing simulation results all the domains and /or surfaces which have an average temperature favourable to the growth of all these species of bacteria having a thermal assigned μ characteristic were carried out. Mohr and Krawiec [28] highlighted typical value of bacteria thermal characteristics, assessed in the range 17.8 ÷ 30.3 kcal/mol. According to these studies that also indicate logarithmic growth rate graphical representation, the μ chosen from the obtained results are 10, 20, 30 kcal/mol, and then the corresponding logarithmic growth rates are listed below as $G_{\mu 10}$, $G_{\mu 20}$ and $G_{\mu 30}$. Tab.2 provides an example of the growth rate sizes for the above bacteria thermal characteristic values , calculated on the typical day of 20 January, at two different times (h 12.00 and h 22.00) for different sub-domains (air volumes, see Fig.4) and for some specific surfaces for book shelving and paper volumes located over them, in particular the empty space on shelving (S1), the back of the books (S2) and the surface overlying the books (S3), as shown in Fig.11. parameters that can decrease the problems of protection of paper material and collections, with cultural value, and maintenance of proper indoor hygiene and air quality also for occupants health. As a matter of fact, one of the main problems for biological diagnostics of the cultural heritage is the non-invasive sampling techniques carrying out. The study of objects/artifacts should be carried out without modifying it, especially if it has small dimensions. Moreover, in many real situations, the microorganisms that caused damage do not always grow in culture under laboratory conditions, even though permanent degradation on paper material has taken place, making diagnoses problematic when using conventional culture-dependent techniques in particular when they must be fast and non-invasive or non-destructive.

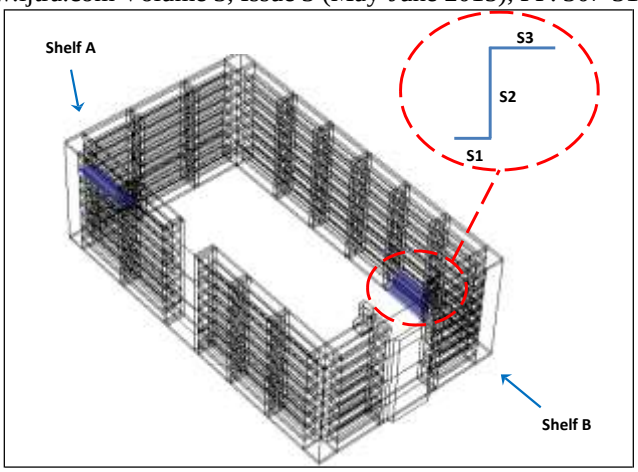


Fig. 11. Location of positions of the representative shelving for growth rates calculation (Shelf A and B) limited to the example of surfaces S1, S2 and S3

Our proposed methodological approach allows the knowledge of when, where and how, the processes responsible for indoor fungal and bacteria pollution, microbial activity increase and significant spores spreading in the environment, due to restrained infiltration presence, draughtiness of building envelope, thermophysical building components behaviour connected to external climatic variations, indoor heat and mass transfer and air flow and circulation in transient conditions, become important and must be limited or eliminated. Our method can also provide the basic guidelines for cultural heritage protection, health hazards detection and then clear rules for the appropriate protection of heritage objects, workers and visitors.

IV. CONCLUSIONS

The presented study revealed that our proposed method can be a useful and not expensive tool to control microclimate

Symbol		S.I. Unit
a_w	Water activity	-
c_p	Specific heat at constant pressure	[J/(kg K)]
k	Turbulent kinetic energy	-
D_w	Vapour diffusivity	[m^2/s]
h	Convective heat transfer coefficient	[W/(m^2·k)]
F	Magnitude of buoyancy force	[N/m^3]
G	Bacteria growth rate	-
I	Identity tensor	-
n	Normal unit vector	-
p	Pressure	[Pa]
R	Constant of ideal gas	[J/(mol·K)]
U □□□*u, v, w*□	Velocity vector	[m/s]
U	Magnitude of velocity vector	[m/s]
t	Time	[s]
T	Temperature	[K]

Greek symbol

□□$_p$	Vapour permeability in air	[kg/(m·s·Pa)]
□	Dissipation rate of turbulent kinetic	-
□	Dynamic viscosity	[Pa·s]
□	Relative humidity	-
□	Thermal conductivity	[W/(m·K)]
□	Bacteria thermal	[kcal/mol]
□	Density	[kg/m^3]
□	Moisture capacity	[kg/m^3]

Subscript

int	Internal
sat	Saturation
T	Turbulent
ext	External

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