Extended summary

Development of measurement procedures for the determination of the distribution of temperature and humidity in the domestic environment and inside building materials.

Curriculum: Ingegneria meccanica e gestionale

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Abstract. A measurement procedure and system for the assessment of the temperature and the humidity in indoor environment as well as inside buildings are reported this thesis.
The researches presented have been carried out in a European project: AXIOMA, whose aim is to develop smart building materials that can provide a controlled release of biocides at precise trigger points to prevent the growth of biological organisms.
It is possible that buildings can be affected by the presence of biological organisms (mostly algae and fungi) which can cause aesthetic, structural and health problems.
Products containing biocide with uncontrolled release today are used to contrast the growth of such biological organisms. The drawback is that high concentrations of biocides can be dangerous for people's health and for the environment.
A smart and controlled release of biocide process, which can increase the mean life of buildings without health's problems, is possible if the temperature and humidity conditions are well know either in the indoor environment either into the materials.
This work, thanks to the studies of temperature and relative humidity carried out in standard indoor scenarios (a bathroom and a kitchen of a house where people live) and the use of a specific measurement procedure, allows the identification of the areas where the conditions for the mold's growth are optimal. Such a large quantity of measured data (temperature and humidity) were not found in literature and it has been used in the AXIOMA project to tune the models and the software tools under development for the preparation of optimal smart materials.
A second important issue dealing with this thesis is the study of temperature and moisture profiles inside the analyzed construction materials: paints, plaster and tiles.
The experimental data have been validated through two analytical models providing temperature and the moisture values inside the materials, when the surface temperature and relative humidity are known.

Keywords. Biocides, mold, temperature, humidity, smart materials.

1 Problem statement and objectives.

No one knows exactly how many homes have mold behind their walls, but according to the best current estimate about 57 percent of European houses have problems of mold [1]. Mold can cause different troubles which can be summarized in three big categories: esthetic, structural and health. The esthetic problem is undoubtedly the less important, however when mold is present on the walls people have to redecorate often and this is surely a cost. The structural damage that mold can lead to in the materials is, of course, more important and lead to higher cost to recover, requiring not only the interview for the reconditioning of the surfaces but also requiring a larger intervention addressed to the materials on which the external materials (tiles, paints, plasters) are applied. But probably the most important consequence of the presence of mold is surely the health problems it can cause. A total of 11% of the entire global burden of diseases has been attributed to unhealthy buildings.
While the indoor environment may contain numerous natural and man- made pollutants, the allergenic impact of biocontaminants, such as dust mites and microfungi, has received particular attention in recent years [1, 2]. The crucial factor for the growth of algae and fungi is the existence of suitable environmental conditions [4], so their suppression must involve the modification of the room temperature and humidity.
From all what just said the necessity to have building materials which can prevent the birth of mold and consequently lengthen the structural properties of the same materials and improve the quality of life of the occupants of the building is evident and can be considered an issue of large interest in the materials and building research area.
The studies of this research have been incorporated in a European project denominated AXIOMA (http://www.axioma-project.eu/) whose initial target was the creation of a range of building products resistant to biological infestation by virtue of incorporating an environmentally acceptable biocide in smart materials with a controlled release.
The experience brings to state that the rooms of the house in which mold is more often present are: the bathroom and the kitchen. For this reason the first task of this research was focused on the determination of the climatic conditions of these rooms during a ‘normal’ use which determinates cycles of temperature and relative humidity, important factor for the growth of mold. The changes in temperature and humidity analyzed inside domestic environments allows to identify the areas at risk of mold growth which could be covered with materials enriched with biocides.
The second task of this work is the determination of temperature and moisture’s distributions inside the four different building materials selected: two types of paints (one for indoor and one for outdoor use), a plaster coating and ceramic tiles. Such building materials were placed in a climatic chamber which was able to reproduce the same temperature and humidity conditions recorded in the bathroom during a shower of 15 minutes, allowing to perform a sort of accelerated testing. The experimental data were validated by two mathematical models relating sample depth and temperature and relative humidity. These relations are the ones needed into the AXIOMA project to be able to determinate the correct value of trigger for the release of biocide which is encapsulated inside the smart materials.
The advantage is that with the selected release mechanisms we are aiming to obtain at least a factor 5 increase in life time with respect to bio-resistivity (>10 years) to achieve the impact required. Simultaneously we want to minimize the concentration of active agents in the product formulation by a similar factor 5. The consequence is that actions can be taken with a gain of money, security and health for the occupants of the rooms.

2 Research planning and activities.

The physical quantities which are of main interest in the preparation of smart building materials able to realize a responsive release of biocide are:

- temperature (T)
- relative humidity (HR).

T and HR are in fact related to the rate of growth of microorganism, creating the ideal conditions for birth and proliferation; in particular it must be reminded that the max growth rate, in laboratory conditions, is obtained at 25 °C and 80-100% of relative humidity for fungi and at 15 °C and 100% of relative humidity for algae [15].
The first aim of this thesis is therefore to investigate which kind of transducers have to be selected for direct measurement of these two quantities in indoor house spaces. The aimed quantities – T and HR – will be measured either in air and at the surface of the materials (ceramics or wall surface) and the measurement range of interest are: 0 – 40°C for temperature and 10-100% for relative humidity.
For the temperature thermocouples K are connected to a National Instrument system board (NI USB-9213). This system was calibrate and its accuracy obtained is: 0.02°C in air and 0.4 °C on the surface were the same installation create a lot mistakes of measurement.
For the humidity two different system are used: a thermohygrometer HD2101.2, with an accuracy of ±3% in the interval of 0-99%, and 4 capacitive sensors SHT75 , with an accuracy of ±4% in the interval of 0-99%. The calibration of the device for the acquisition of humidity is done of the factory of the instrumentations because in the university's laboratory is not possible to have a good calibration.
With these systems relations of temperature and humidity at the center of the room and on the surface (points 1-2 in the fig.1) have been studied as well as the ones between the surface and into the material (points 2-3 fig.1).

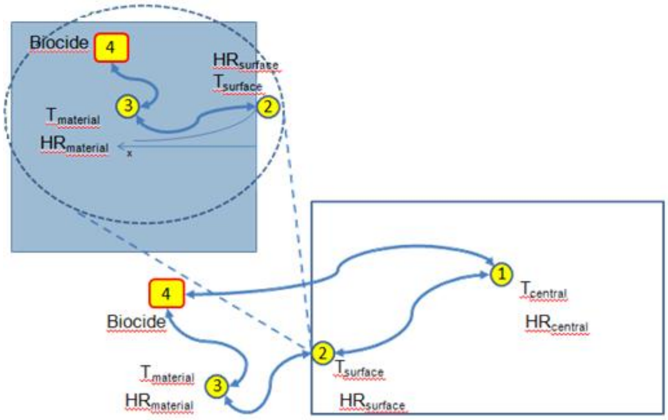

Figure 1: A schematic representation of the relations studied.

The environment analyzed are a bathroom and a kitchen where the sensors are placed in strategic points where the variations of temperature and relative humidity are more significant (fig. 2).

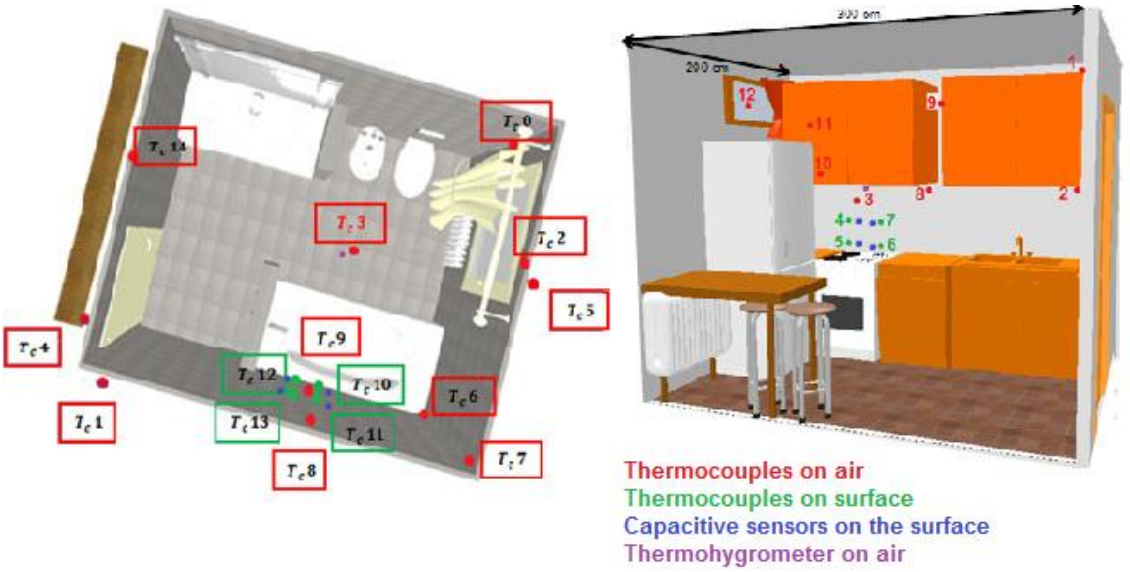

Figure 2: The position of the sensors in the two environments selected.

The variation of temperature and moisture are studied into: paint, plasters and tiles. The samples of such materials were instrumented and were put into a climatic chamber, CH250 Angelantoni, which has run cycles of temperature and relative humidity equal replicating the ones recorded in the bathroom. To reproduce a realistic situation the samples were isolated on three side in order to receive the heat flux only from the top surface. In this way the relation between temperature and relative humidity on the surface and a different depth for the buildings material are studied.

3 Analysis and discussion of main results.

The first important activity was the definition of the measurement set-up and procedure to be used for the data collection on the two selected environments; in particular such set-up was required to guarantee adequate metrological characteristics (sensitivity, measurement range, uncertainty, repeatability and robustness), but also to allow easy installing time (see paragraphed 2).

It was decided to focus the attention on two specific indoor places: the bathroom and the kitchen, where the presence of molds is most significant.

For these indoor ambient, a specific, intense and continuous experimental activity was implemented in order to firstly collect significant data (temperature and relative humidity) from the standard daily use of the two selected environments. The bathroom and the kitchen are normally used by four people and in each of the two environments a significant event has been chosen. In particular the event studied in the bathroom is a shower of 15 minutes while in the kitchen the event is to bring to the boil two liters of water for 5 minutes.

The data recorded are not present in the literature and are summarized in the table 1 for the bathroom and table 2 for the kitchen:

Table 1. Experimental data recorded in the bathroom where ΔT ΔHr are the variation of temperature and relative humidity recorded during the shower t_c the time required to came back the initial value.

Conditions		**Temperature**			**Relative Humidity**		
		N. Samples	ΔT [°C]	t_c [s]	N. Samples	ΔHr [%]	t_c [s]
Conditions of test		302400	0,48±0.02	16941	58429	47,5±3	2418
Heating	ON	113934	0,51±0.02	18989	2961	50±3	987
	OFF	53997	0,39±0.02	17999	3369	60±3	1123
External	August	370440	0,52±0.02	41160	-	-	-
Temperature	November	166446	0,45±0.02	18494	-	-	-
Window	Opens	22620	0,57±0.02	3770	14070	47,5±3	1055
	Closes	113934	0,51±0.02	18989	102012	47,5±3	15557

Table 2: Experimental data recorded in the kitchen where ΔT ΔHr are the variation of temperature and relative humidity recorded during the shower tc the time required to came back the initial value.

Conditions	**Temperature**			**Relative Humidity**		
	N. Samples	ΔT [°C]	t_c [s]	N. Samples	ΔHr [%]	t_c [s]
Conditions of test	64764	7.99±0.02	2446	20832	21.2±3	1256

From the data recorded the following important conclusions must be taken into consideration:

- The larger temperature and relative humidity variations take place in the bathroom, which should be considered the part of the indoor environment where the biological growth can most probably take place;
- Differently from to the bathroom, the kitchen, is subjected to smaller temperature and relative humidity variations, but locally, in particular in the area of the fire place and over it, the temperature variations as well as the RH variations can be very large;
- In both the indoor environments considered, the ideal temperature and RH values at which the fungi and algae growth is maximized are reached during the representative activities analyzed (a shower some water and the boiling); so during events, in the kitchen as well as in the bathroom, algae and fungi are very likely to grow;
- Absence of ventilation, wall height, as well the use of the central heating systems are proved to be influencing parameters which in combination can create larger T and RH variations, for longer time;

In the table 3 summarized the linear relations that are studied for the different points of the bathroom, where the variations of temperature are more significant, with the center of room and the surface (see fig.2)

Table 3: linear relations studied for the different points of the bathroom, where the variations of temperature are more significant, with the center of room and the surface

Sensors placed in the top part of the room				
Sensor Number	**The regression line**			
	Slope	**Intercept**	**Mean Slope**	**Mean Intercept**
0	0	22.94	0.61±0.05	8.81±0.01
2	0.69	7.00		
7	0.84	3.45		
14	0.91	1.84		
Sensors placed in the mid part of the room				
Sensor Number	**The regression line**			
	Slope	**Intercept**	**Mean Slope**	**Mean Intercept**
6	0.59	9.03	0.38±0.05	13.96±0.01
8	0.35	14.61		
9	0.2	18.25		
Sensors placed around the shower tap				
Sensor Number	**The regression line**			
	Slope	**Intercept**	**Mean Slope**	**Mean Intercepts**
10	-0.3	24.52	-0.2±0.4	23.88±0.01
11	-0.1	23.62		
12	-0.14	23.88		
13	-0.25	24.15		

For the humidity the relation between the air and the surface is a second grade curve: $f(x)=-0.01*x^2+1.69*x-15.07$.
How already said a study for temperature and humidity into the material was done.
To validate the experimental data recorded two are the models present in literature: one for the temperature [34], and Hansen's model for the moisture [35]. In literature, however, there are not coefficient for the Hansen's model for the relation of moisture with the depth in the tiles. I elaborated these coefficients for the tiles and the equation of the model is: $moisture=49.5*abs(1-\ln(Rh)/4.8)^{(-1/22.2)}$.
Then the validation of experimental temperature data a experimental model is elaborated to find a relation between depth and temperature into the studied materials: $T_{depth}=a*x^2+b*x+T_{superficial}$, where the parameters a and b change with the materials.

4 Conclusions

The first aim of this thesis was to obtain measurement data of indoor environmental conditions for selected end-user application areas. In particular, for indoor environments, where the smart materials developed in the AXIOMA project could be installed, it intended to determine what the typical thermal and humidity environment conditions are. Such indoor conditions could be, in fact, the ones creating the potentially riskfull conditions and consequently allow the growth of biological organisms.
From both the indoor environments explored, a bathroom and a kitchen, data have been transferred (and will continue to be transferred during the following 6 months) in order to support the modeling activities. In particular, for the analysis of the indoor environmental

conditions the empirical relations between the temperature measured in different parts of the room (center of the room) and the external surface of the smart materials (middle of the wall) will be used for the construction of the software tool.
The second aim of this thesis is to develop a profile of temperature and moisture into the buildings materials: two paints, a coating and the tiles.
Also in this case the first step was the individuation of the transducers and of the measurement chain to be used during the accelerate test in the climatic chamber, and the understanding of how this new configuration can influence the precision of the measurement.
After the acquisition of the data of temperature and moisture, these are validated through the model present in the literature. After the validation, which assures the goodness of the data recorded, an empirical model between the depth and the temperature and moisture recorded by the transducers placed at the different level into the material is developed. For the tiles, in literature there is not a Hansen's model to describe the moisture, so in this job I elaborated and determinate the parameters of the equation.
These empirical relations allow to obtain the value of temperature and moisture at different depths by knowing only the value on the surface of the building materials.
Also these relations have been transferred in order to support the development of the software which in this way can model also the release of biocide after the activation of the trigger.
Safely the measurements of the moisture into the materials need an postponement, in particular it is necessary to have more points of measurement in the thickness of materials. To reach this aim smaller capacitive sensors are necessary for the moisture. At this time the model can be modified and can better represent the real profile of the moisture in the materials.

References

[1] A.B. Murray, A. B. (1985). Sensitization to house dust mites in different climate areas. *Journal of Allergy and Clinical Immunology 76*, 108-112.
[2] T.Platts-Mills, M.C.(1987). Immunology, allergic disease and environmental control. *Journal of allergy and clinical immunology 80*,755-775.
[3] M.J. Cunningham (1996), Controlling dust mites psychometrically, a review for scientists and engineers, *Indoor air 6*, 249-258.
[4] M.J. Colloff (1987), Effects of temperatures and relative humidity on development times and mortality of eggs from laboratory and wild populations of the European house-dust mite Dermatophagoides pteronyssinus (Acari: Pyroglyphidae), *Experimental and applied acarology 3*, 279-289.
[5] Adan OCG and Samson RA*,* Fungal disfigurement of interior finishe"Singh J Building mycology. Management of decay and health in buildings*, Chapman and Hall,* London, UK, pp. 130-158.
[6] UNI EN ISO 7730: Ergonomics of the thermal environment- Analytical determination and interpretation of thermal comfort using calculation of the PMV and PDD indices and local thermal comfort criteria.
[7] The ISO8996: Ergonomics of the thermal environment- Determination of metabolic rate.
[8] ISO 7726: Ergonomics of the thermal environment – Instruments for measuring physical quantities.
[9] M.Masi, Special Tender for works of Green Building.
[10] Cole GT and Samson RA*,* "Patterns of development in conidial fungi", *Pitman, London, UK.*
[11] Samson RA, Houbraken J, Thrane U, Frisvad JC and Andersen B (2010) "Food and indoor fungi", *CBS laboratory manual series 2.* Centraalbureau voor Schimmelcultures, Utrecht, the Netherlands.

[12] McGregor HJ, Miller JD, Rand T and Salmon J "Mold ecology: recovery of fungi from certain moldy building materials".
[13] Prezant B, Weekes DM and Miller JD, Recognition, evaluation, and control of indoor mold. AIHA, Fairfax, VA, USA.
[14] Brasel TL, Douglas DR, Wilson SC and Strauss DC "Detection of airborne Stachybotrys chartarum macrocyclic trichothecene mycotoxins on particulates smaller than conidia", *Appl. Environ Microbiol 71*: 114-122.
[15] Olaf C.G. Adan, Robert A. Samson, Fundamentals of mold growth in indoor environments and strategies for healthy living.
[16] Directive 98/8/EC of the European Parliament and of the Council of 16 February 1998.
[17] BB. .Sandel, R.H. Dumas, P.A. Turley (2005). Antimicrobial protection for plastic structures, *US patent 053397*.
[18] F.G. Burton, D.A. Ctaldo, J.F.Cline, W.F. Skiens. (1992), Long-term control of root growth, *US patent 5116414*.
[19] M.Edge, N.S. Allen , D. Turner, J.Robinson, K.Seal (2001), Progress in Organic coatings 43, 10-17.
[20] C.J. Brinker and G.W. Scherer, "Sol-gel Science", Academic Press, London, 1990.
[21] Y.Liu, P. Laks, P. Heiden (2003), *Holzforschung 57*, 135-139.
[22] Y.Liu, P. Laks, P. Heiden (2002), *Journal of Applied Polymer Science 86*, 596-621.
[23] B.D. Ratner, A.S.Hoffman, F.J.Schoen, J.E. Lemons (2004), Biomaterials Science: An introduction to Materials in Medicine, Elsevier Academic Press New York.
[24] M. Nydén, C.Fant, K. Holmberg, L.Swanson (2006), Method and use of acidified modified polymers to bind biocides in paint, *patet WO 096129, 2006*.
[25] Polymer matrix for extending vase life of cutflowers: EP 1643832,Anti microbial envelopes: WO 03/101196.
[26] Inducible release vehicles: US 2007/035099.
[27] Baker H.D., Ryder E.A., Baker N.H, Temperature Measurement in Engineering Vol 1 e 2.
[28] Bailey, N.P.,(1931), The response of thermocouples, *Mechanical Engineering. Vol. 53*, No. 1, p.797
[29] Mc Cann, J.A, (1962), Temperature Measurement Theory, Office of technical Service, Department of Commerce, Washington, DC .
[30] Han-Taw Chen, Shen-Yih Lin, Lih-Chuan Fang, (2001), Estimation of surface temperature in two-dimensional inverse heat conduction problems, *International journal of Heat and Mass Transfer 44*, 1455-1463.
[31] Evaluation of measurement data Supplement 1 to the "Guide to the expression of uncertainty in measurement"Propagation of distributionsusing a Monte Carlo method.
[32] M.Isabel M. Torres, Vasco Peixoto de Freitas, Treatment of rising damp in historical buildings: wall base ventilation.
[33] Paul H.Baker, Graham H. Galbraith, R. Craig McLean, Chris H.Sanders, The development of instrumentation for the measurement of relative humidity within building microenvironments.
[34] Norme per l'attuazione del Piano energetico nazionale in materia di uso razionale dell'energia, di risparmio energetico e di sviluppo delle fonti rinnovabili di energia, *Legge 9 gennaio 1991 n.10.*
[35] K.K. Hansen (1986), Sorption isotherms, a catalogue, Technical Report 162/86, Buildings materials Laboratory, Technical University of Denmark.
[36] N.M.M. Ramos, J.M.P.Q. Delgado, V.P. de Freitas, Influence of finishing coatings on hygroscopic moisture buffering in building elements.
[37] H.M. Kunzel (1995), Simultaneous Heat and Moisture Transport in Building Components, Fraunhofer IRB Verlag Suttgart, ISB 3-8167-4103-7.
[38] W. Bich (2012), From errors to probability density functions. Evolution of the concept of measurement Uncertainty, *IEEE transactions on instrumentation and measurement*, Vol. 61, no.8.

[39] P.da S. Hack and C.S. ten Caten, Measurement Uncertainty: Literaruature Review and Research trends (2012), *IEEE transactions on instrumentation and measurement*, Vol. 61, no.8.

[40] A. Ferrero and S. Salicone, Uncertainty: only one mathematical approach to its evaluation and expression?, *IEEE transactions on instrumentation and measurement*, Vol. 61, no.8.

[41] L. Pel (1995), Moisture transport in porous building materials.

[42] M.I.M.Torres, V.P.de Freitas (2007), Treatment of rising damp in historical buildings: wall base ventilation, *ScienceDirect, Building and Enverimental 42,* pp 424-435.

[43] A. Holm and H.M.Kunzel (1999), Combined effect of temperature and humidity on the detoriation process of insulation matirials in etics, *Building Physics in the Nordic Countries*

[44] H.J. Steeman, A. Janseens, J. Carmeliet, M. De Paepe, (2009) Modelling indoor air and hygrothermal wall interaction in building simulation: Comparison between CFD and a well-mixed zonal model, Building and Environment 44, 572-583.

[45] N. Mendes and P.C. Philippi (2005), A method for predicting heat and moisture transfer through multilayered walls based on temperature and moisture content gradients, *International journal of Heat and Mass transfer 48, 37-51.*

[46] H.-T. Chen, S-Y. Lin, L.-C. Fang (2001), Estimation of surface temperatuer in two-dimensional inverse heat conduction problems, *International journal of Heat and Mass transfer 44,1455-1463.*

[47] M.Masi ,"Capitolato Speciale d'Appalto per opere di Bioedilizia"

[48] Coordinamento tecnico per la sicurezza nei luoghi di lavoro, "Microclima, aerazione e illuminazione nei luoghi di lavoro. Requisiti standard. Indicazioni operative e progettuali. Linee guida", 1 giugno 2006.

[49] Direttiva 98/8/CE del Parlamento Europeo e del Consiglio, 16 febbraio 1998, in materia di "Immissione sul mercato dei biocidi".

[50] Doebelin Ernest O. (2008), Strumenti e metodi di misura, seconda edizione, McGraw-Hill.

[51] Hospitals in Europe Link for Infection Control through Surveillance project management by Institute of Hygiene and Epidemiology (Brussels), CBO (Utrecht), Statens Seruminstitut (Copenhagen), Université Claude Bernard (Lyon), "HELICS PROTOCOL SURGICAL WOUND INFECTION SURVEILLANCE".

[52] Il Progetto INF-OSS, "Prevenzione e Controllo delle Infezioni nelle Organizzazioni Sanitarie e Socio-sanitarie"finanziato dal Centro per la Prevenzione e Controllo delle Malattie (CCM) del Ministero della Salute, 2006-2008.

[53] Legge ordinaria n° 373/76, 7 giugno 1976, "Norme per il contenimento del consumo energetico per usi termici negli edifici", pubblicata sulla Gazzetta Ufficiale Italiana n° 148.

[54] Ministero della sanità e dipartimento della prevenzione, "La tutela e la promozione della salute negli ambienti confinati" , 27 settembre 2001.

[55] Vivian Loftness, Bert Hakkinen, Olaf Adan, & Aino Nevelainen, "Elements that contribute to healthy building design", Environmental Health Perspectives , volume 115, number 6, june 2007, pagg. 965-970.

[56] Walter Rudin, *Real and Complex Analysis*, Mladinska Knjiga, McGraw-Hill, 1970.