University of Pisa – School of Engineering
Dept. Of Energy, Systems, Territory and Construction Engineering (DESTeC)
Lighting and Acoustic Laboratory

Research title:

Indoor environmental quality assessment: study of innovative strategies based on the multi-criteria analysis

PhD student: Michele Rocca (e-mail: michele.rocca.au@gmail.com)

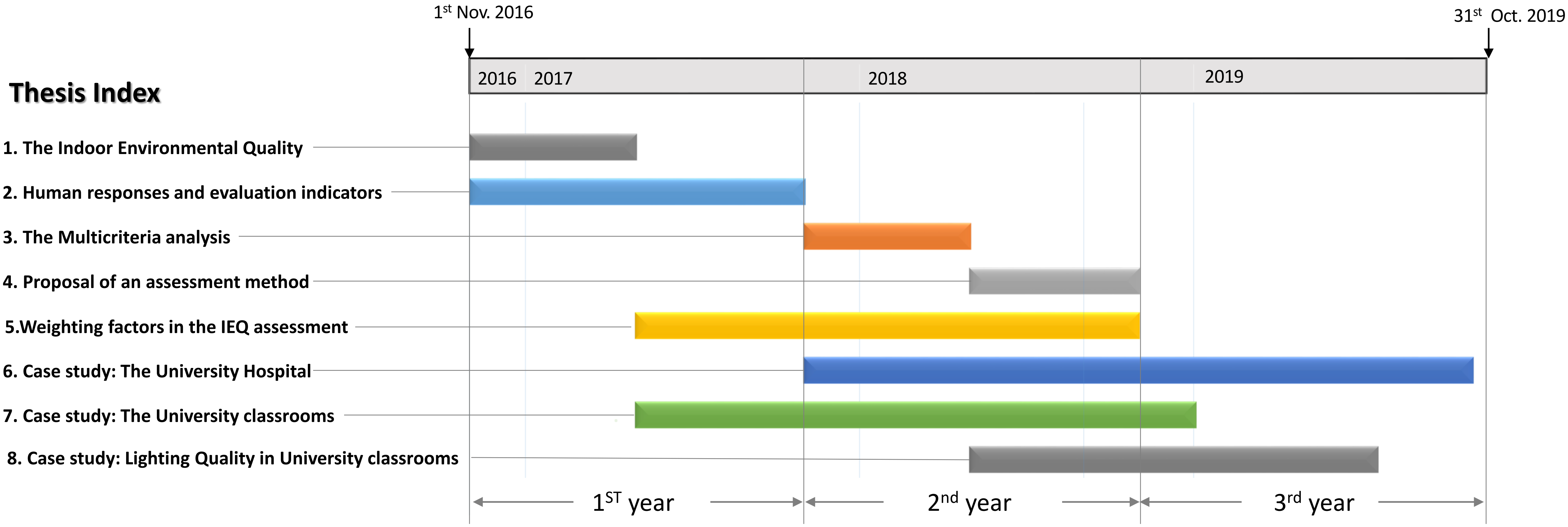
Tutors: prof. Fabio Fantozzi, ing. Francesco Leccese

PhD course in Energy, Systems, Territory and Construction Engineering
(XXXII cycle, 2016) – Presentation of final dissertation draft – 13 November 2019

TABLE OF CONTENTS

Thesis Index

TIMELINE OF THE ACTIVITIES



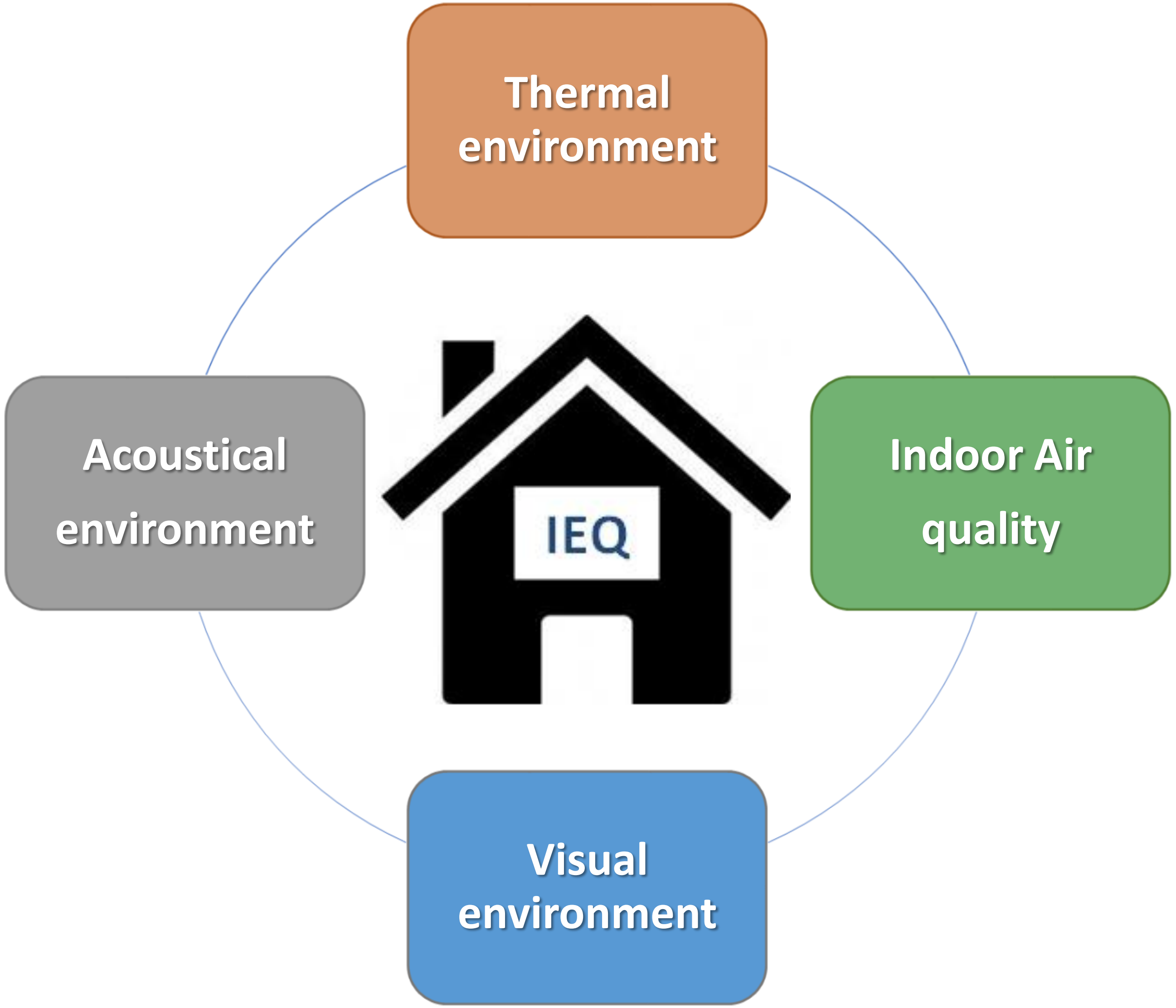
INTRODUCTION

RESEARCH QUESTION

The aim of the research was to create a method for IEQ assessment in existing buildings aimed at identifying critical aspects and creating criticality rankings.

INDOOR ENVIRONMENTAL QUALITY (IEQ)

"The Indoor Environmental Quality (IEQ) is a perceived indoor experience about the building indoor environment that includes aspects of design, analysis, and operation of energy efficient, healthy, and comfortable buildings" [ASHRAE TC 1.6]



Energy performance labelling

Quantitative and qualitative evaluation of **energy performance** of buildings

PAST

Energy performance labelling

Quantitative and qualitative evaluation of **energy performance** of buildings

PRESENT

Environmental Sustainability certification

Quantitative and qualitative evaluation of **comfort**, **energy performance** and **energy consumptions** of buildings.

PAST	PRESENT	FUTURE
Energy performance labelling	**Environmental Sustainability certification**	**Overall well being certification**

PAST

Energy performance labelling

Quantitative and qualitative evaluation of **energy performance** of buildings

PRESENT

Environmental Sustainability certification

Quantitative and qualitative evaluation of **comfort**, **energy performance** and **energy consumptions** of buildings.

FUTURE

Overall well being certification

Quantitative and qualitative evaluation of **all factors** that affect the **person's well-being**

A COMPREHENSIVE APPROACH TO WELL-BEING

INTERNATIONAL WELL BUILDING INSTITUTE

THE WELL BUILDING STANDARD

SEVEN CONCEPTS FOR HEALTHIER BUILDINGS

AIR | WATER | NOURISHMENT | LIGHT | FITNESS | COMFORT | MIND

INTERNATIONAL
WELL
BUILDING
INSTITUTE

AIR
14 FEATURES
4 preconditions
10 optimizations

WATER
8 FEATURES
3 preconditions
5 optimizations

NOURISHMENT
13 FEATURES
2 preconditions
11 optimizations

LIGHT
8 FEATURES
2 preconditions
6 optimizations

MOVEMENT
12 FEATURES
2 preconditions
10 optimizations

THERMAL COMFORT
7 FEATURES
1 precondition
6 optimizations

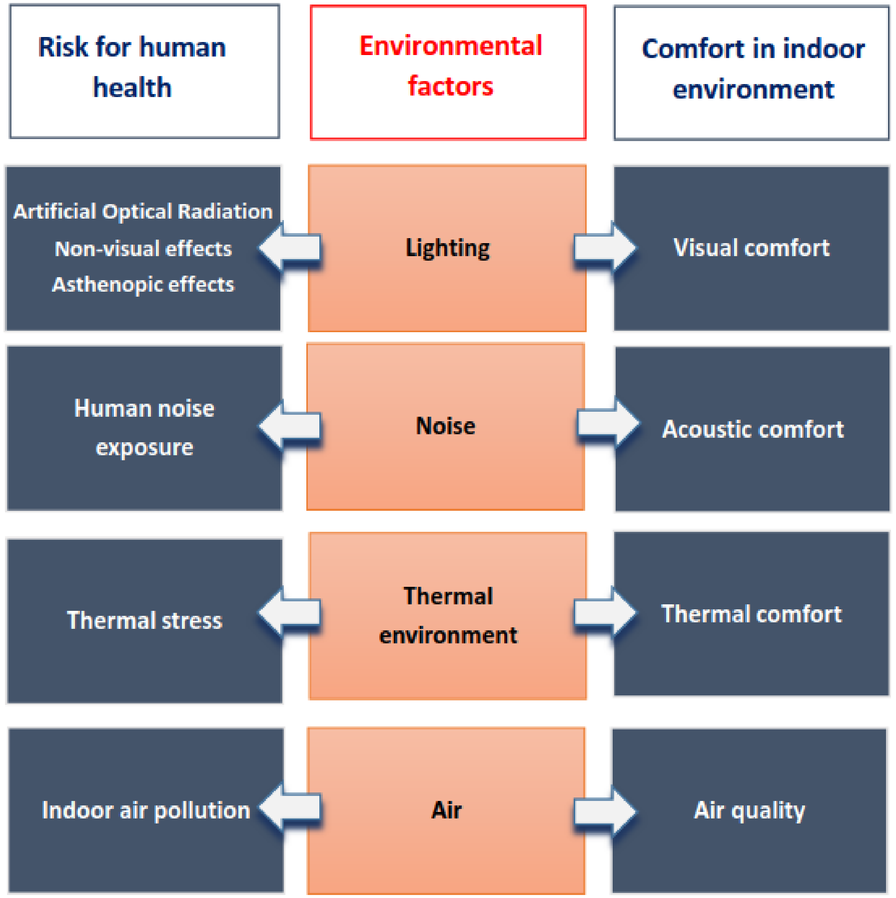
SOUND
5 FEATURES
1 precondition
4 optimizations

MATERIALS
14 FEATURES
3 preconditions
11 optimizations

MIND
15 FEATURES
2 preconditions
13 optimizations

COMMUNITY
16 FEATURES
3 preconditions
13 optimizations

Health and wellbeing in indoor environment



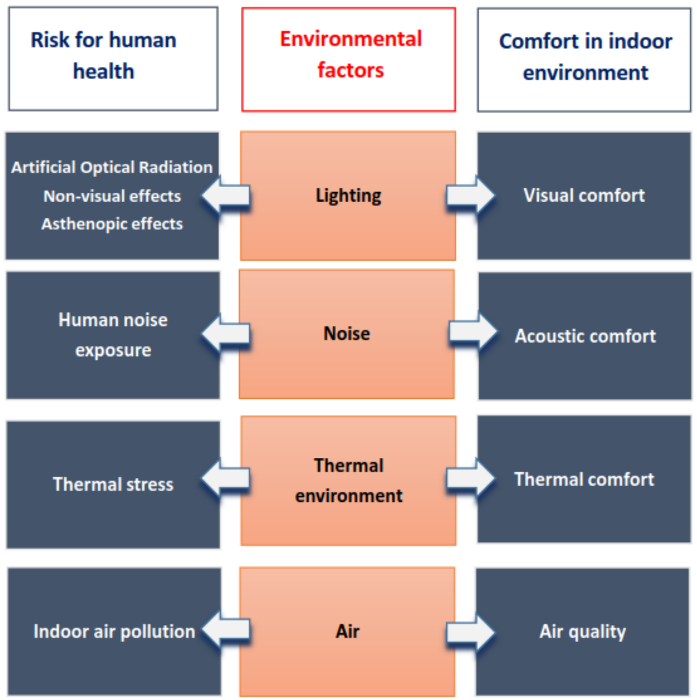
The human perception of environment depends on four basic factors:

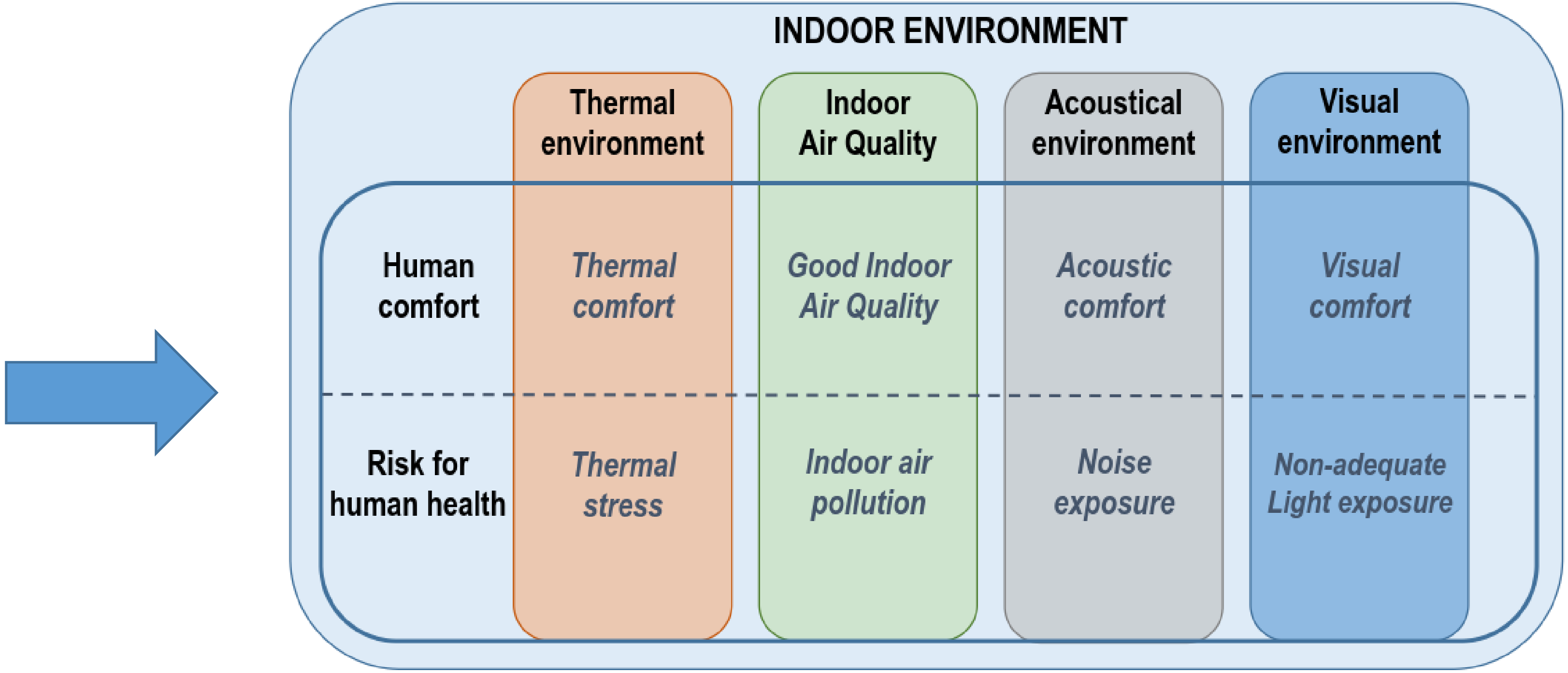
- ✓ **lighting**,
- ✓ **noise**,
- ✓ **thermal environment** and
- ✓ **air**.

Each of these can be evaluated from two counterpoised point of view:

- ✓ the **risk for human health**;
- ✓ the **human comfort**.

Health and wellbeing in indoor environment

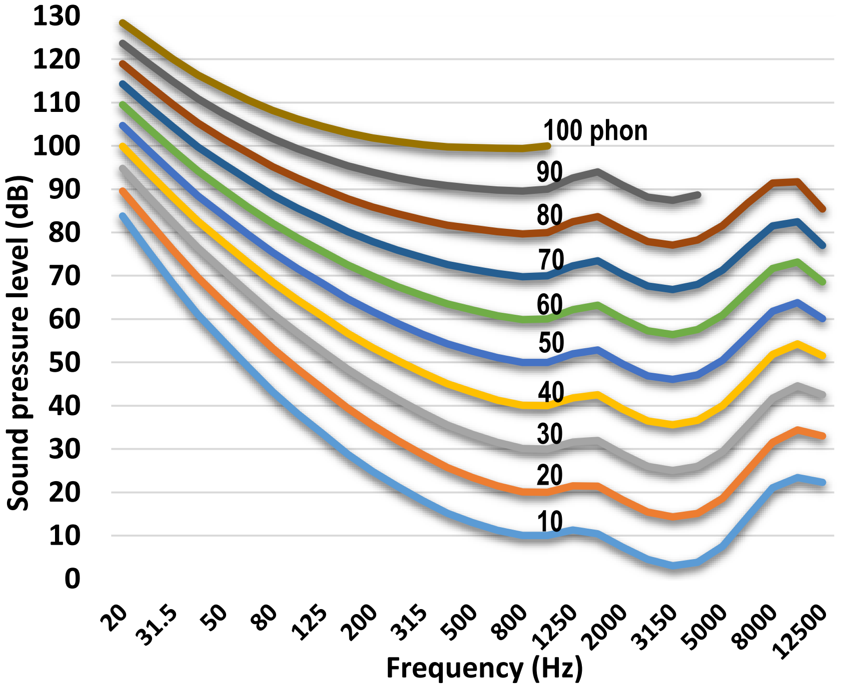




HUMAN RESPONSE TO ENVIRONMENTAL FACTORS AND EVALUATION INDICATORS

HUMAN RESPONSE MODELS

Example of human response to sound



Fonte: ISO 226, 2007

RISK FOR HUMAN HEALTH INDICATORS

Example of Indoor air pollution

Fonte: https://sandium.com/air-quality/sick-building-syndrome.html

HUMAN COMFORT INDICATORS

Example of thermal comfort

Fonte: https://www.cctech.co.in/

Thermal Environment

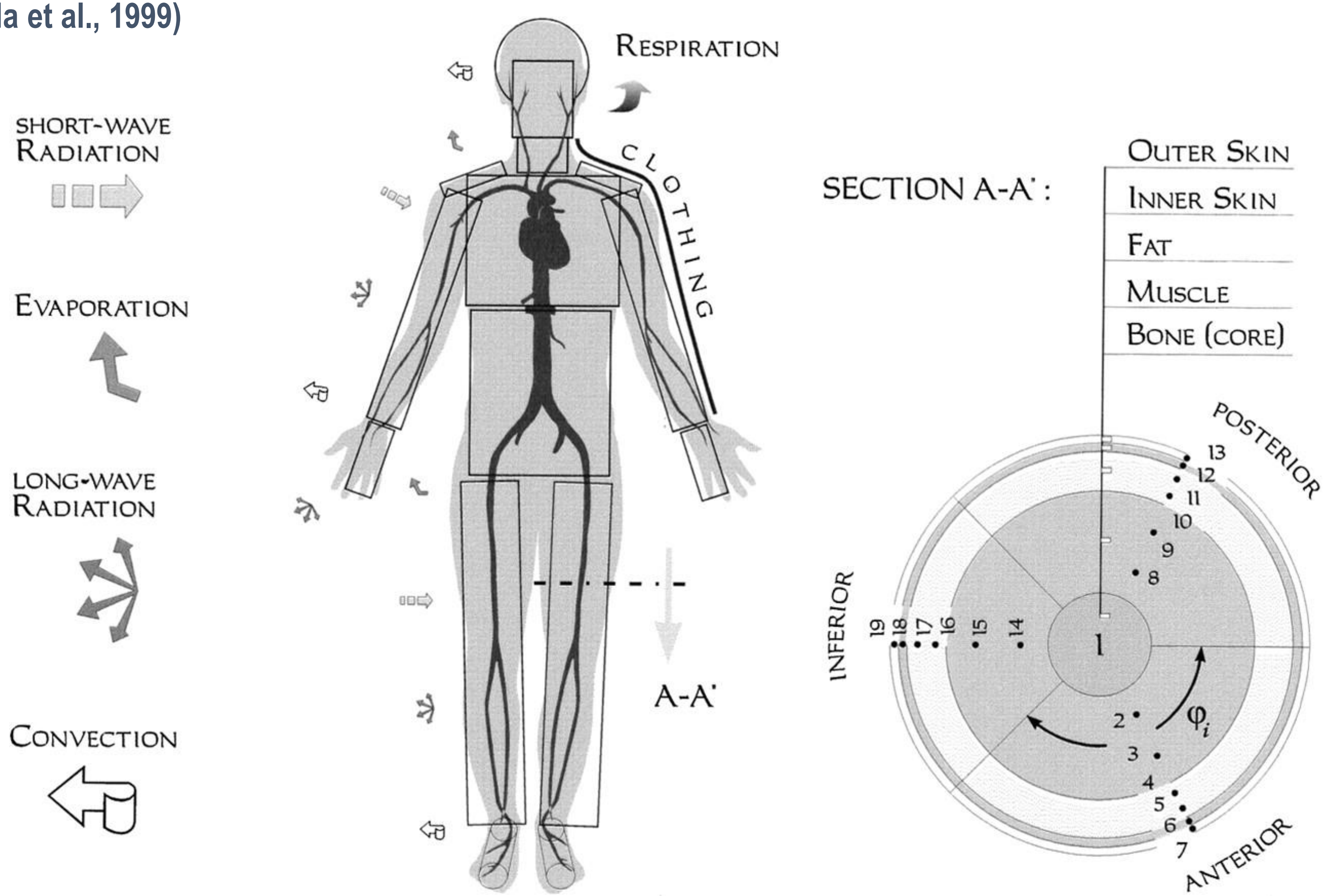
The human exposure on environmental factors occurs mainly through the senses.
For each factors there are models for estimate the **human sensitivity** (i.e. photopic spectral sensitivity curve and isophonic curves) and models for estimate the **human regulation** (i.e. Physiological and behavioural temperature regulation).

Example: for the thermal perception have been realized different schematization of the human body:

- ✓ **One-cylinder model**:
  - Model-two node model (Gagge, 1973);
  - Multilayer model (Wyndham and Atkins, 1969);
  - Three part model (Kawashima and Yamamoto, 1977).
- ✓ **Multi-segment model**:
  - Stolwijck model (Stolwijck et al., 1966);
  - Tanabe model (Tanabe et al., 1995);
  - Fiala model (Fiala et al. 1999)
  - Berkley model (Huzeniga et al., 2001).
- ✓ **Model with external thermoregulation system**:
  - Webb model (Webb et al., 1968).

MULTI-SEGMENT MODEL

Fiala model (Fiala et al., 1999)



Thermal Environment

Risk for human health indicators

People working in uncomfortably hot and cold environments are more likely to behave unsafely because their ability to make decisions and/or perform manual tasks deteriorates. **When the body's means of controlling its internal temperature starts to fail heat stress occurs**.

- ✓ **WBGT** (Wet bulb globe temperature);
- ✓ **PHS** (Predicted Heat Strain);
- ✓ **IREQ** (Required Clothing Insulation).

Thermal comfort

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) defined it as "**the condition of the mind in which satisfaction is expressed with the thermal environment**"

There are two approach to evaluate the thermal comfort:

- ✓ The **heat balance approach** based on the thermal balance between the human body and the environment. P.O. Fanger (1970), proposed a method to evaluate the thermal comfort with an energy balance equation, with the aim to predict the mean thermal sensation of a group of people (PMV, PPD).
- ✓ The **adaptive approach** derives from research focused on the real acceptability of the thermal environment, which is strictly connected to the context, and to the expectation and behaviour of the occupants.

In literature there are **more than 50 indicators** for the evaluation of the thermal comfort from 1905 to present.

Thermal Environment

Heat balance equation:

$$S = M - W - R - C - C_k - E_d - E_{sw} - E_{ve} - C_{ve}$$

where:

S is the storage of heat in the body (W);

M è la metabolic heat generation (always positive in a living organism), (W);

W is the heat power lost in the environment (W);

R is the heat power lost by radiation (W);

C is the heat power lost by convection (W);

C_k is the heat power lost by conduction (W);

C_k is the heat power lost by conduction (W);

C_k is the heat power lost by conduction (W);

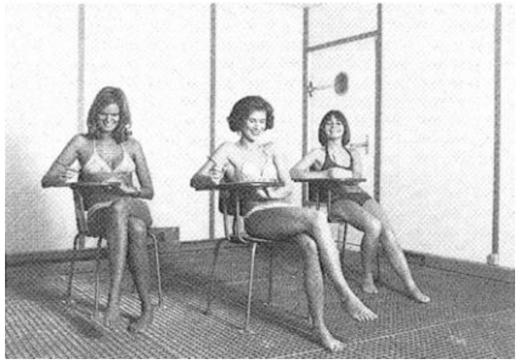
E_d is the heat power lost by vapour diffusion through the skin or transpiration (W);

E_{sw} is the heat power lost by sweating through the skin (W);

E_{ve} is the heat power lost by breathing as latent heat (W);

C_{ve} is the heat power lost by breathing as sensible heat (W).

Thermal Environment



Fanger equation

Predicted Mean Vote

$$PMV = (0.303e^{-0.036M} + 0.028)\{(M-W) - 3.05\times10^{-3}[5733 - 6.99(M-W) - p_a]$$
$$-0.42[(M-W) - 58.15] - 1.7\times10^{-5}M(5867 - p_a) - 0.0014M(34\text{-}t_a)$$
$$-3.96\times10^{-8} f_{cl}[(t_{cl}+273)^4 - t_{mr}+273)^4 - f_{cl}h_c(t_{cl} - t_a)\}$$

where:

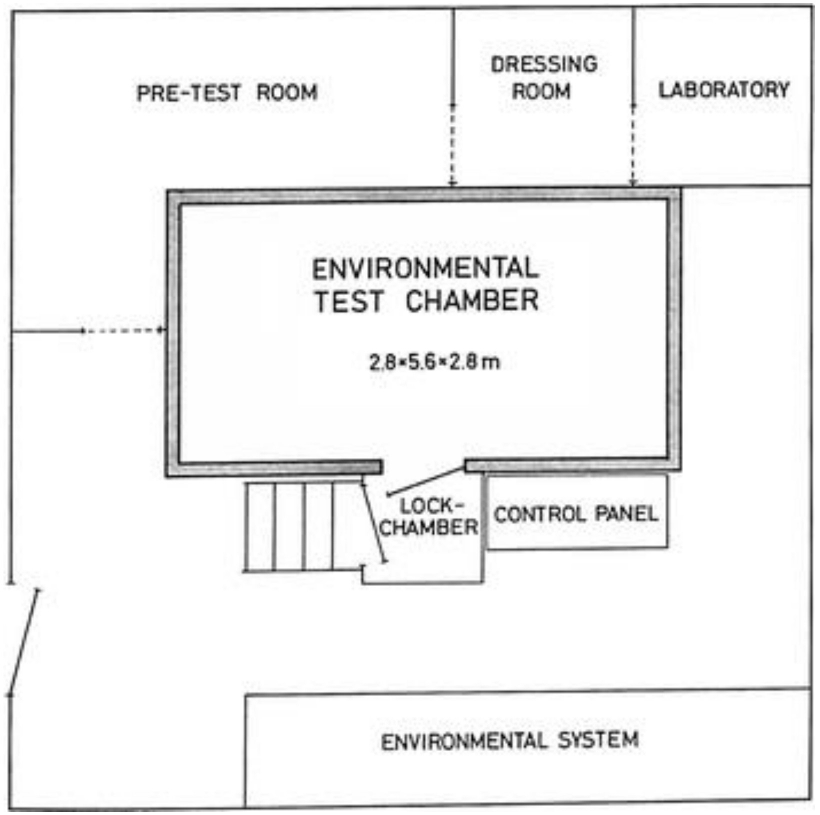
t_{cl} is the mean temperature of the external surface of the dressed human body (°C);

t_a is the air temperature (°C);

t_r is the mean radiant temperature (°C);

f_{cl} is the coefficient of the clothing area (equal to the ratio between the surface of the dressed body and the surface of the naked body

h_c is the coefficient of air-clothing convection (W/m^{2}K)



Thermal Environment

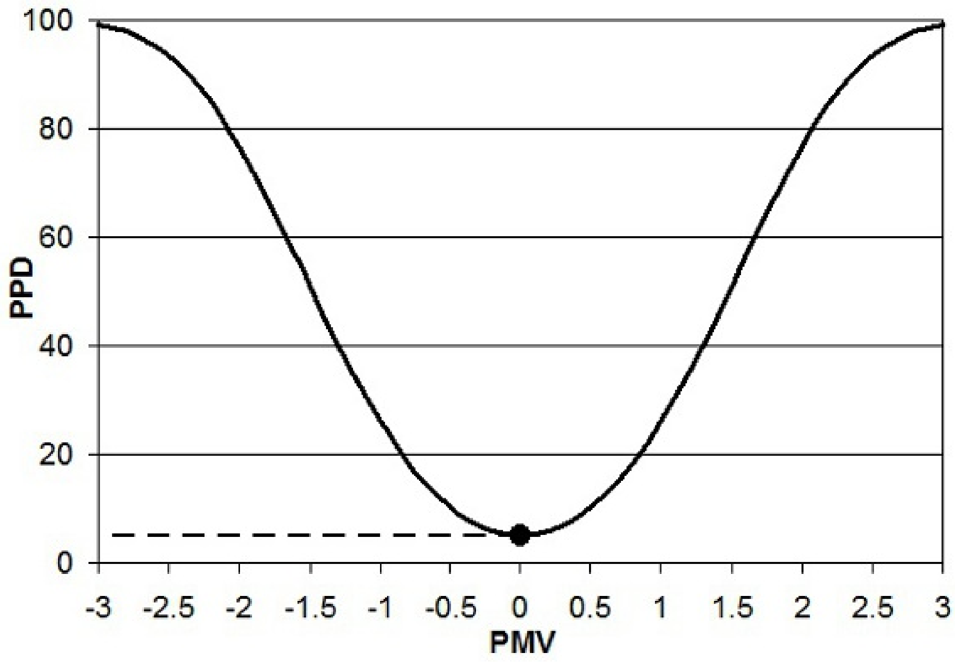
Fanger equation

Predicted Mean Vote

$$PMV = (0.303e^{-0.036M} + 0.028)\{(M-W) - 3.05\times10^{-3}[5733 - 6.99(M-W) - p_a]$$
$$-0.42[(M-W) - 58.15] - 1.7\times10^{-5}M(5867 - p_a) - 0.0014M(34\text{-}t_a)$$
$$-3.96\times10^{-8}f_{cl}[(t_{cl}+273)^4 - t_{mr}+273)^4 - f_{cl}h_c(t_{cl}-t_a)\}$$

Predicted Percentage of Dissatisfied:

$$PPD = 100 - 95\, exp - (0.03353\, PMV^4 + 0.2179\, PMV^2)$$



Thermal Environment

- 15 thermal models
- 36 thermal stress indicators
- 48 thermal comfort indicators

Indoor air quality

- 37 air pollutants
- 17 air pollutants limit values
- 9 indoor air quality indicators

Acoustical Environment

- Equal loudness curves
- 9 noise exposure indicators
- 39 acoustic comfort indicators

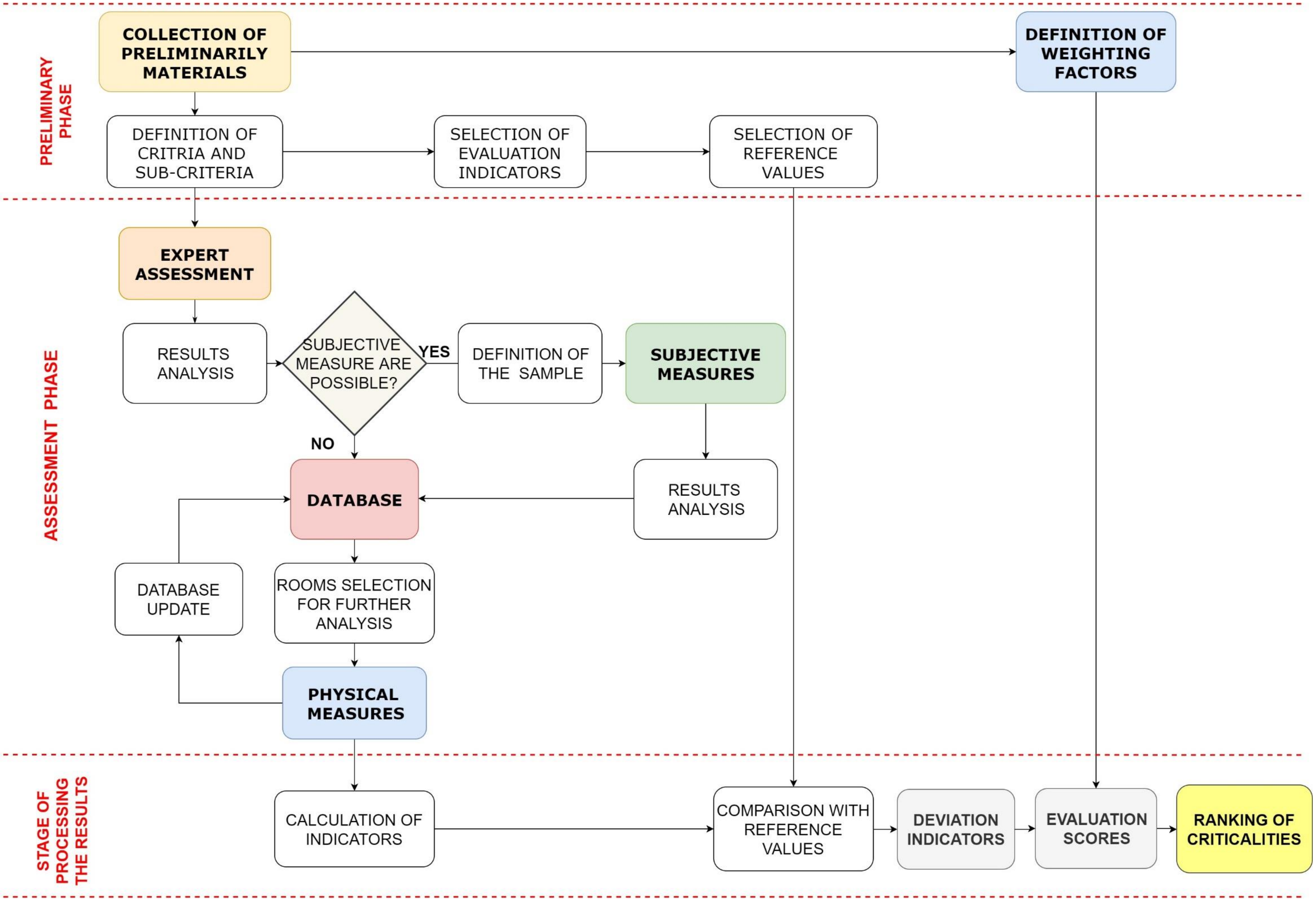
Visual Environment

- 11 Human eyes sensitivity curves
- 15 lighting exposure indicators
- 42 Visual comfort indicators

For each factor, the indicators have been classified according to the application areas.

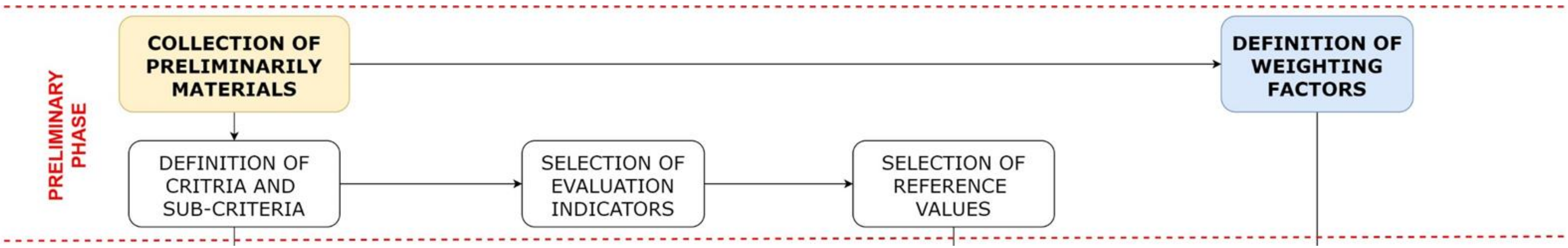
PROPOSED ASSESSMENT METHOD

EVALUATION PROCEDURE



The proposed assessment method

Preliminary phase



Collection of preliminary materials

Definition of Criteria and Sub-Criteria

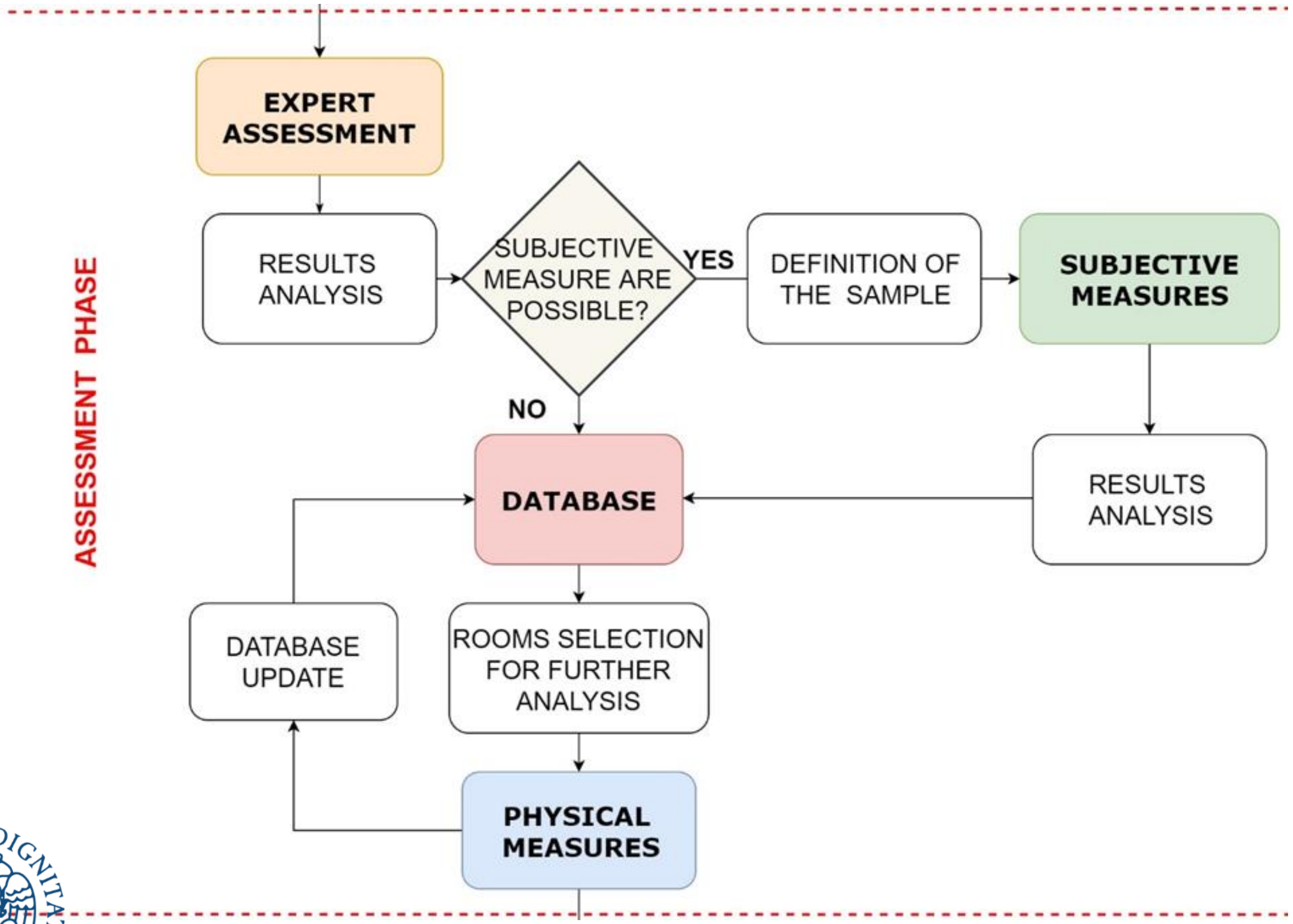
Selection of the evaluation indicators and reference/benchmark values

Definition of the weighting factors

The proposed assessment method

Assessment phase

«A typical environmental survey involves measuring the physical environmental conditions and also the subjective responses of people exposed to the environment» *[EN ISO 28802: 2008[1]]*



Expert assessment / Observation assessment

↓

Checklist

Measurement of subjective response

↓

Questionnaire

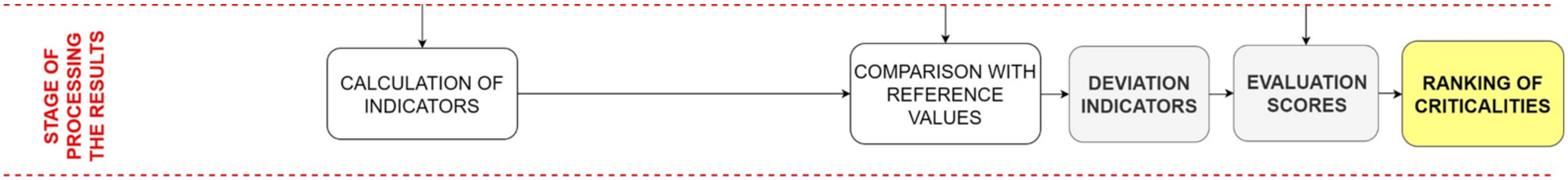
Measurement of the physical environment

↓

Field measurements

The proposed assessment method

Processing of the results



Deviation Indicator

$$DI = \frac{|P_R - P_B|}{P_B}$$

(P_R = Real value; P_B = Benchmarck value)

Normalized Deviation Indicator

$$DI_n = \frac{DI}{DI_{max}}$$

(DI_{max} = Maximum theoretical value of DI)**

Evaluation Score

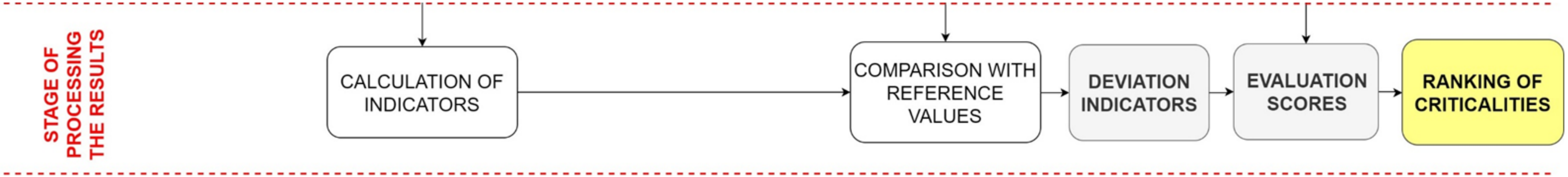
$$FS = W \times DI_n$$

(W = weight)

** If it is not possible to set a maximum value (P_R can theoretically vary up to infinity or in any case up to very large values) DI_{max} is assumed equal to 9 which correspond the case in which the real value is an order of magnitude greater than the benchmark value.

The proposed assessment method

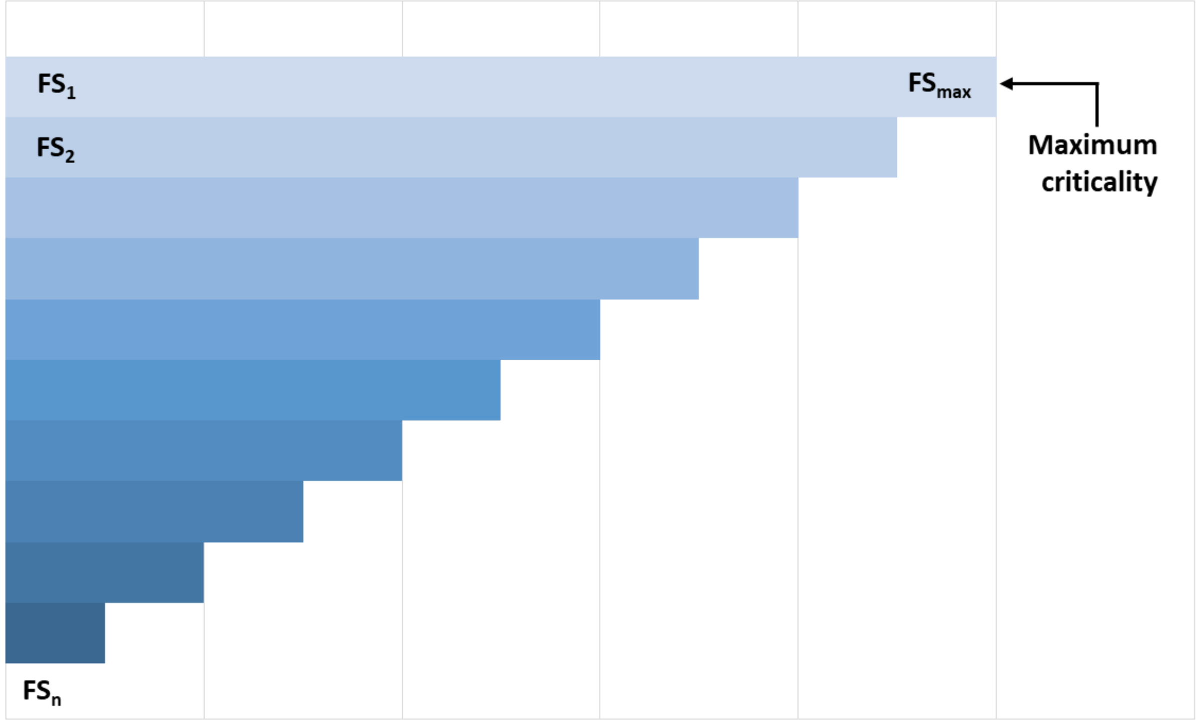
Processing of the results



Evaluation Score

FS = 1 **Maximum criticality**

FS = 0 **No criticality**



WEIGHTING FACTORS IN IEQ ASSESSMENT

BIBLIOGRAPHIC RESEARCH

1° Step

Search by keywords

«Indoor Environmental Quality»; «Thermal comfort»; «Indoor air quality»; «Visual comfort»;«Acoustic comfort».

+ 100,000 papers

2° Step

Search by keywords

«Thermal comfort» + «Indoor air quality» + «Visual comfort» + «Acoustic comfort»
«Indoor Environmental Quality» + «IEQ model»
«Indoor Environmental Quality» + «IEQ index»
«Indoor Environmental Quality» + «assessment scheme»
«Indoor Environmental Quality» + «weighting»

200 papers

3° Step

Limitation of the publication period

2002-2018

Selection of articles in which weights are proposed for the IEQ overall evaluation.

20 papers

Ref.	Study and year of publication	Period of administration	Country	Nr. of respondents	Type of buildings
[1]	Chiang and Lai (2002)	Not declared	Taiwan	12	Dwellings
[2]	Mui and Chan (2005)	1992-1995	Hong Kong (China)	422	Offices
[3]	Humphreys (2005)	1998-1999	France, Greek, Portugal, Sweeden, UK	4655	Offices
[4]	Wong et al. (2008)	Not declared	Hong Kong	293	Offices
[5]	Astolfi and Pellerey (2008)	Not declared	Italy	852	Schools
[6]	Lai et al. (2009)	Not declared	Hong Kong (China)	125	Dwellings
[7]	Lai and Yik (2009)	Not declared	Hong Kong (China)	563	Dwellings
[8]	Bluyssen et al. (2011)	2003-2004	Germany, Switzerland, Italy, Finland, Denmanrk, Portugal, the Netherlands, UK	5732	Offices and dwellings
[9]	Cao et al. (2012)	2008-2009	China	500	Schools and Offices
[10]	Lee et al. (2012)	Not declared	Hong Kong	312	Schools
[11]	Ncube and Riffat (2012)	2010	UK	68	Office
[12] [13] [14]	Frontczak et al. (2012) Wargocki et al. (2012) Heinzerling et al. (2013)	2001-2011	USA	52980	Offices
[15]	Catalina and Iordache (2012)	-	-	-	-
[16]	Frontczak et al. (2012b)	2011	Denmark	645	Dwellings
[17]	Ghita and Catalina (2015)	2013-2014	Romania	708	Schools
[18]	Xue et al. (2016)	2013-2014	Hong Kong (China)	482	Dwellings
[19]	Middelhurst et al. (2018)	Not declared	UK	27	Office
[20]	Tahsildoost and Zomorodian (2018)	2016-2017	Iran	842	Schools

SELECTED PAPERS

[1] Chiang, C.-M., Lai, C.-M., **2002**. A study on the comprehensive indicator of indoor environment assessment for occupants' health in Taiwan. **Building and Environment** 37, 387–392.

[2] Mui, K.W., Chan, W.T., **2005**. A New Indoor Environmental Quality Equation for Air-Conditioned Buildings. **Architectural Science Review** 48, 41–46.

[3] Humphreys, M.A., **2005**. Quantifying occupant comfort: are combined indices of the indoor environment practicable? **Building Research & Information** 33, 317–325.

[4] Wong, L.T., Mui, K.W., Hui, P.S., **2008**. A multivariate-logistic model for acceptance of indoor environmental quality (IEQ) in offices. **Building and Environment** 43, 1–6.

[5] Astolfi, A., Pellerey, F., **2008**. Subjective and objective assessment of acoustical and overall environmental quality in secondary school classrooms. **The Journal of the Acoustical Society of America** 123, 163–173.

[6] Lai, A.C.K., Mui, K.W., Wong, L.T., Law, L.Y., **2009**. An evaluation model for indoor environmental quality (IEQ) acceptance in residential buildings. **Energy and Buildings** 41, 930–936.

[7] Lai J.H.K., Yik F.W.H., **2009**. Perception of importance and performance of the indoor environmental quality of high-rise residential buildings. **Building and Environment** 44, 352-360.

[8] Bluyssen, P.M., Aries, M., van Dommelen, P., **2011**. Comfort of workers in office buildings: The European HOPE project. **Building and Environment** 46, 280–288.

[9] Cao, B., Ouyang, Q., Zhu, Y., Huang, L., Hu, H., Deng, G., **2012**. Development of a multivariate regression model for overall satisfaction in public buildings based on field studies in Beijing and Shanghai. **Building and Environment** 47, 394–399.

[10] Lee, M.C., Mui, K.W., Wong, L.T., Chan, W.Y., Lee, E.W.M., Cheung, C.T., **2012**. Student learning performance and indoor environmental quality (IEQ) in air-conditioned university teaching rooms. **Building and Environment** 49, 238–244.

[11] Ncube, M., Riffat, S., **2012**. Developing an indoor environment quality tool for assessment of mechanically ventilated office buildings in the UK – A preliminary study. **Building and Environment** 53, 26–33.

[12] Frontczak, M., Schiavon, S., Goins, J., Arens, E., Zhang, H., Wargocki, P., **2012**. Quantitative relationships between occupant satisfaction and satisfaction aspects of indoor environmental quality and building design: Indoor environmental quality. **Indoor Air** 22, 119–131.

[13] Wargocki, P., Frontczak, M., Schiavon, S., Goins, J., Arens, E., Zhang, H., **2012**. Satisfaction and self-estimated performance in relation to indoor environmental parameters and building features. Proceedings of the 10th International Conference on Healthy Buildings, 1(1), 1-7.

[14] Heinzerling, D., Schiavon, S., Webster, T., Arens, E., **2013**. Indoor environmental quality assessment models: A literature review and a proposed weighting and classification scheme. **Building and Environment** 70, 210–222.

[15] Catalina, T., Iordache, V., **2012**. IEQ assessment on schools in the design stage. **Building and Environment** 49, 129–140.

[16] Frontczak M., Andersen R.V., Wargocki P., **2012**. Questionnaire survey factors influencing comfort with indoor environmental quality in Danish housing. **Building and Environment** 50, 56-64.

[17] Ghita S.A., Catalina T., **2015**. Energy efficiency versus indoor environmental quality in different Romanian countryside schools. **Energy and Buildings** 92, 140-154.

[18] Xue P., Mak C.M., Ai Z.T., **2016**. A structured approach to overall environmental satisfaction in high-rise residential buildings. **Energy and Buildings** 116, 181-189.

[19] Middlehurst, G., Yao, R., Jiang, L., Deng, J., Clements-Croome, D., Adams, G., **2018**. A preliminary study on post-occupancy evaluation of four office buildings in the UK based on the Analytic Hierarchy Process. **Intelligent Buildings International** 1–13.

[20] Tahsildoost M., Zomorodian Z.S., **2018**. Indoor environment quality assessment in classrooms: An integrated approach. **Journal of Building Physics** 42(3), 336-362.

TYPES OF ANALYSIS AND SELECTED FACTORS

Type of analysis	Study	Analysed aspects	Ref.
Analytic Hierarchy Process (AHP)	Chiang et al. (2002)	Thermal comfort, Acoustics, Indoor air quality, Lighting, Electromagnetic fields.	[1]
	Lai and Yik (2009)	Thermal comfort, Noise, Air cleanliness, Odour.	[7]
	Middelhurst et al. (2018)	Thermal quality, Noise quality, Indoor air quality, Lighting quality, Ventilation quality	[19]
Multiple linear regression	Mui and Chan (2005)	Thermal comfort, Aural comfort, Indoor air quality, Visual comfort (not significant).	[2]
	Humphreys (2005)	Warmth, Humidity, Noise, IAQ, Lighting, Air movement.	[3]
	Bluyssen et al. (2011)	Thermal comfort, Noise, Air quality, Light.	[8]
Multivariate linear regression	Cao et al. (2012)	Thermal environment, Acoustic environment, Air quality, Luminous environment.	[9]
	Ncube and Riffat (2012)	Thermal comfort, Acoustics, Indoor air quality, Lighting.	[11]
	Heinzerling et al. (2013)	Thermal comfort, Acoustics, Indoor air quality, Lighting.	[14]
	Xue et al. (2016)	Thermal comfort and Air quality (ensemble), Acoustics, Lighting.	[18]
Multivariate linear regression + non-parametric Spearman correlation	Frontczak et al. (2012b)	Thermal environment, Sound quality, Air quality, Light quality.	[16]
Multiple non-linear regression model	Catalina and Iordache (2012)	Thermal comfort, Acoustic comfort, Indoor air quality, Visual comfort.	[15]
Multivariate logistic model	Wong et al. (2008)	Thermal environment, Equivalent noise level, Indoor air quality, Illumination level.	[4]
	Lai et al. (2009)	Thermal comfort, Noise level, Indoor air quality, Illumination.	[6]
	Lee et al. (2012)	Thermal environment, Aural environment, Indoor air quality, Visual environment.	[10]
Pearson correlation analysis	Astolfi and Pellerey (2008)	Thermal, Acoustical, Indoor air, Visual.	[5]
	Tahsildoost and Zomorodian (2018)	Thermal comfort, Acoustic comfort, Indoor air quality, Visual comfort.	[20]
Proportional ordinal logistic regression and multivariate linear regression	Frontczak et al. (2012), Wargocki et al. (2012)	Amount of space, Noise level, Visual privacy, Colour and texture, Easy on interaction, comfort of furnishing, Temperature, Sound privacy, Air quality, Building maintenance, Furniture adjustability, Visual comfort, building cleanliness, workplace cleanliness.	[12] [13]
Analysis of specific questions	Ghita and Catalina (2015)	Thermal comfort, Acoustics, Indoor air quality, Lighting.	[17]

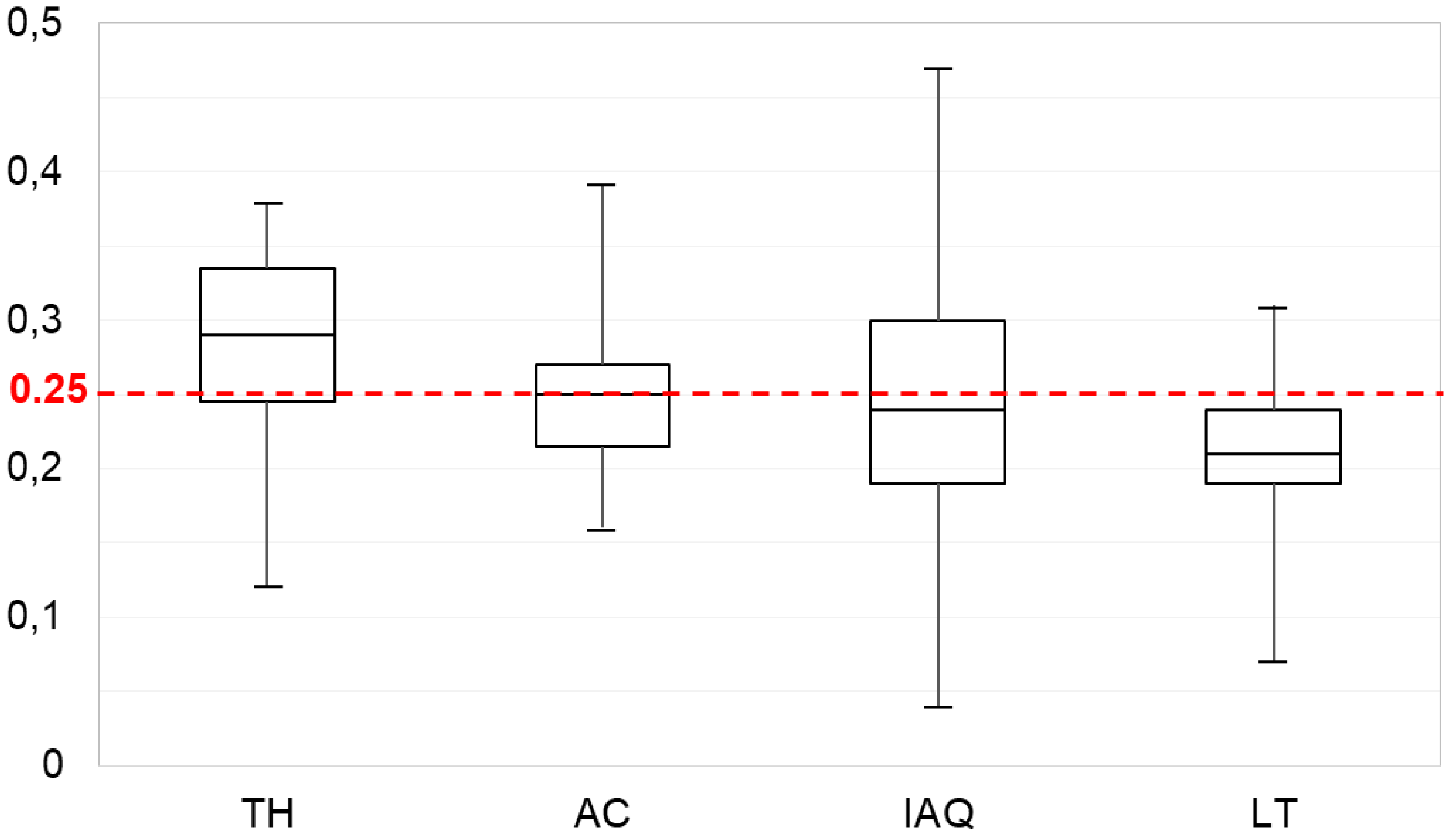
WEIGHTS PROPOSED IN LITERATURE

Type of buildings	Ref	Study	TH	IAQ	AC	LT
Dwellings	[1]	Chiang et al. (2002)	0.16	0.22	0.15	0.12
	[6]	Lai et al. (2009)	22.05	1.61	11.77	21.86
	[7]	Lai and Yik (2009)	0.23	0.20	0.23	-
	[16]	Frontczak et al. (2012b)	0.48	0.64	0.52	0.52
	[18]	Xue et al. (2016)	0.36		0.22	0.25
Offices	[2]	Mui and Chan (2005)	0.42	0.09	0.28	-
	[3]	Humphreys (2005)	0.22	0.05	0.13	0.05
	[4]	Wong et al. (2008)	6.09	4.88	4.74	3.70
	[8]	Bluyssen et al. (2011)	0.55	0.46	0.49	0.44
	[11]	Ncube and Riffat (2012)	0.30	0.36	0.18	0.16
	[12] [13]	Frontczak et al. (2012) Wargocki et al. (2012)	1.16	1.14	1.27	1.09
	[14]	Heinzerling et al. (2013)	0.12	0.20	0.39	0.29
	[19]	Middelhurst et al. (2018)	0.34	0.13	0.15	0.27
Schools	[9]	Cao et al. 2012 [cit]	0.32	0.12	0.22	0.17
	[15]	Catalina and Iordache (2012)	0.25	0.25	0.25	0.25
	[10]	Lee et al. (2012)	1.16	0.96	1.99	1.07
	[17]	Ghita and Catalina (2015)	0.27	0.30	0.19	0.24
	[20]	Tahsildoost and Zomorodian (2018)	0.34	0.08	0.26	0.31
	[5]	Astolfi and Pellerey (2008)	0.50	0.32	0.39	0.29
			0.32	0.31	0.50	0.25

NORMALIZED WEIGHTS PROPOSED IN LITERATURE

Type of buildings	Ref	Study	TH	IAQ	AC	LT
Dwellings	[1]	Chiang et al. (2002)	0.24	0.34	0.24	0.18
	[6]	Lai et al. (2009)	0.38	0.04	0.38	0.20
	[7]	Lai and Yik (2009)				
	[16]	Frontczak et al. (2012b)	0.22	0.30	0.24	0.24
	[18]	Xue et al. (2016)				
Offices	[2]	Mui and Chan (2005)				
	[3]	Humphreys (2005)	0.29	0.47	0.17	0.07
	[4]	Wong et al. (2008)	0.31	0.25	0.24	0.19
	[8]	Bluyssen et al. (2011)	0.28	0.24	0.25	0.23
	[11]	Ncube and Riffat (2012)	0.30	0.36	0.18	0.16
	[12] [13]	Frontczak et al. (2012) Wargocki et al. (2012)	0.25	0.24	0.27	0.23
	[14]	Heinzerling et al. (2013)	0.12	0.20	0.39	0.29
	[19]	Middelhurst et al. (2018)	0.38	0.15	0.17	0.30
Schools	[9]	Cao et al. 2012 [cit]	0.38	0.14	0.27	0.21
	[15]	Catalina and Iordache (2012)	0.25	0.25	0.25	0.25
	[10]	Lee et al. (2012)	0.22	0.18	0.39	0.21
	[17]	Ghita and Catalina (2015)	0.27	0.30	0.19	0.24
	[20]	Tahsildoost and Zomorodian (2018)	0.34	0.08	0.26	0.31
	[5]	Astolfi and Pellerey (2008)	0.33	0.21	0.26	0.19
			0.21	0.23	0.37	0.19

BOX PLOT OF THE NORMALIZED WEIGHTS PROPOSED IN LITERATURE



A PRELIMINARY STUDY

A preliminary study was carried out in order to **develop the evaluation procedure** and to verify the calculation methods of weighting factors.

In order to determine the weights to be attributed to environmental factors in university environments, three subjective survey campaigns were carried out and two different analysis techniques were applied.

1	2	3
Multiple Linear Regression	**AHP**	**AHP**
from **acceptance questionnaire**	from **ranking list**	from **pair wise comparison**
Sample: 911 students	**Sample: 458 students**	**Sample: 65 students**
Period: May 2016 – May 2018	**Period: Sept. 2017 – Sept. 2018**	**Period: Sept. 2018 – Dec. 2018**

Preliminary study on University classrooms

5 university classrooms of the School of Engineering of Pisa.

Extended administration period and **repeated survey** several times in different seasons.

The **aim** is to remove the dependence of the results on specific deficiencies of the single classroom.

C1

Teaching room
S= 156 m^2
V= 512 m^3
N= 139 seats

C2

Teaching room
S= 186 m^2
V= 910 m^3
N= 142 seats

C3

Teaching room
S= 190 m^2
V= 550 m^3
N= 160 seats

C4

Laboratory
S= 215 m^2
V= 613 m^3
N= 84 seats

C5

Teaching room
S= 216 m^2
V= 745 m^3
N= 216 seats

1. Multiple Linear Regression from acceptance questionnaire

Questionnaire on the evaluation of environmental quality perceived within the classroom.

Characteristics:

- 5 parts;
- 10 closed-ended questions;
- 5-point Likert scale;
- Use of verbal scale.

Sample: 911 students

Age: 21.3 years (SD=1.85 y)

Period: May 2016 – May 2018

QUESTIONARIO DI VALUTAZIONE DEL COMFORT AMBIENTALE INTERNO

Data: __/__/_____ Aula: ___________

Età: ____________ Sesso: M☐ F☐ Anno di corso ________________

Parte A. Global

	Insufficiente	Scarso	Sufficiente	Buono	Eccellente
1. **Ai fini del comfort ambientale interno,** come valuta il livello complessivo di benessere percepito nell'aula durante le ore di lezione?	☐	☐	☐	☐	☐

Parte B. Thermal comfort (TH)

	Insufficiente	Scarso	Sufficiente	Buono	Eccellente
2. ..., come valuta il livello di temperatura nell'aula?	☐	☐	☐	☐	☐
3. ..., come valuta il grado di umidità?	☐	☐	☐	☐	☐

Parte C. Indoor air quality (IAQ)

	Insufficiente	Scarso	Sufficiente	Buono	Eccellente
4. ..., come valuta il ricambio d'aria per ventilazione naturale?	☐	☐	☐	☐	☐

Parte D. Acoustics (AC)

	Insufficiente	Scarso	Sufficiente	Buono	Eccellente
5. ..., come valuta l'isolamento acustico dai rumori esterni?	☐	☐	☐	☐	☐
6. ..., come valuta l'isolamento acustico dai rumori provenienti dagli ambienti adiacenti?	☐	☐	☐	☐	☐
7. ..., come valuta la percezione della voce del docente?	☐	☐	☐	☐	☐

Parte E. Lighting (LT)

	Insufficiente	Scarso	Sufficiente	Buono	Eccellente
8. ..., come valuta l'illuminazione dell'ambiente (illuminazione naturale e artificiale mista)?	☐	☐	☐	☐	☐
9. ... come valuta il grado di schermatura della luce naturale?	☐	☐	☐	☐	☐
10. ..., come valuta il grado di schermatura degli apparecchi di illuminazione da fenomeni di abbagliamento diretto durante l'osservazione della lavagna?	☐	☐	☐	☐	☐

Note:____

1. Multiple Linear Regression from acceptance questionnaire

Questionnaire on the evaluation of environmental quality perceived within the classroom.

Characteristics:

- **5 parts;**
- **10 closed-ended questions;**
- **5-point Likert scale;**
- **Use of verbal scale.**

In the post-processing phase, a numerical scale was associated to the verbal scale

Verbal scale	Very Bad	Poor	Sufficient	Good	Excellent
Numeric scale	1	2	3	4	5

QUESTIONARIO DI VALUTAZIONE DEL COMFORT AMBIENTALE INTERNO

Data: __/__/_____ Aula: ___________

Età: ___________ Sesso: M☐ F☐ Anno di corso _______________

Parte A. Global

	Insufficiente	Scarso	Sufficiente	Buono	Eccellente
1. **Ai fini del comfort ambientale interno,** come valuta il livello complessivo di benessere percepito nell'aula durante le ore di lezione?	☐	☐	☐	☐	☐

Parte B. Thermal comfort (TH)

	Insufficiente	Scarso	Sufficiente	Buono	Eccellente
2. ..., come valuta il livello di temperatura nell'aula?	☐	☐	☐	☐	☐
3. ..., come valuta il grado di umidità?	☐	☐	☐	☐	☐

Parte C. Indoor air quality (IAQ)

	Insufficiente	Scarso	Sufficiente	Buono	Eccellente
4. ..., come valuta il ricambio d'aria per ventilazione naturale?	☐	☐	☐	☐	☐

Parte D. Acoustics (AC)

	Insufficiente	Scarso	Sufficiente	Buono	Eccellente
5. ..., come valuta l'isolamento acustico dai rumori esterni?	☐	☐	☐	☐	☐
6. ..., come valuta l'isolamento acustico dai rumori provenienti dagli ambienti adiacenti?	☐	☐	☐	☐	☐
7. ..., come valuta la percezione della voce del docente?	☐	☐	☐	☐	☐

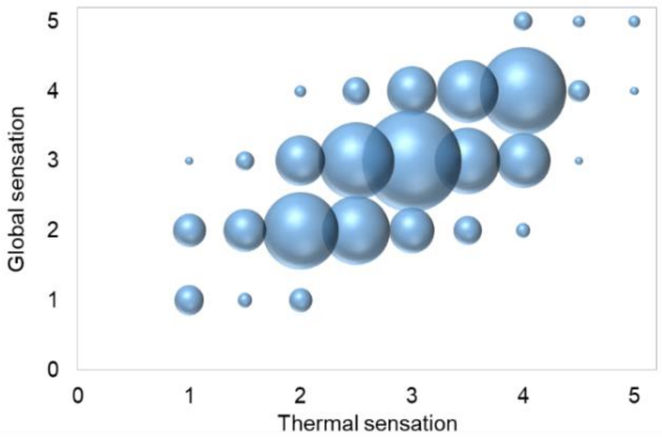
Parte E. Lighting (LT)

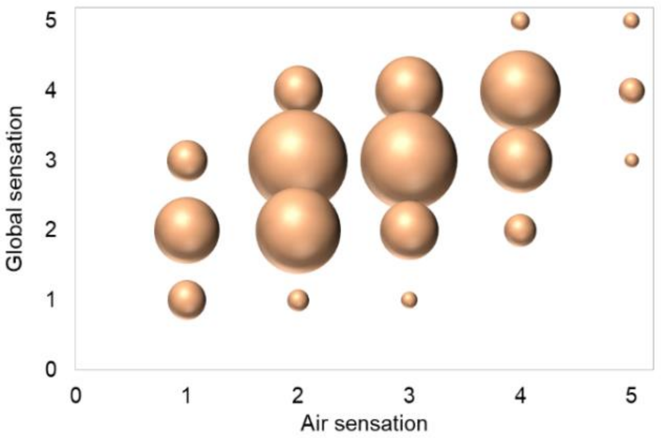
	Insufficiente	Scarso	Sufficiente	Buono	Eccellente
8. ..., come valuta l'illuminazione dell'ambiente (illuminazione naturale e artificiale mista)?	☐	☐	☐	☐	☐
9. ... come valuta il grado di schermatura della luce naturale?	☐	☐	☐	☐	☐
10. ..., come valuta il grado di schermatura degli apparecchi di illuminazione da fenomeni di abbagliamento diretto durante l'osservazione della lavagna?	☐	☐	☐	☐	☐

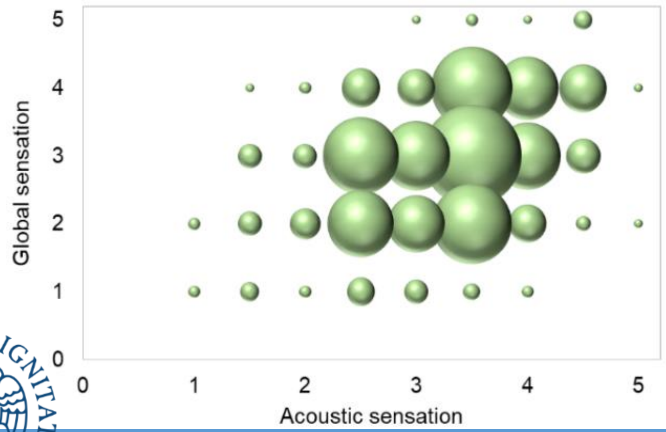
Note:____

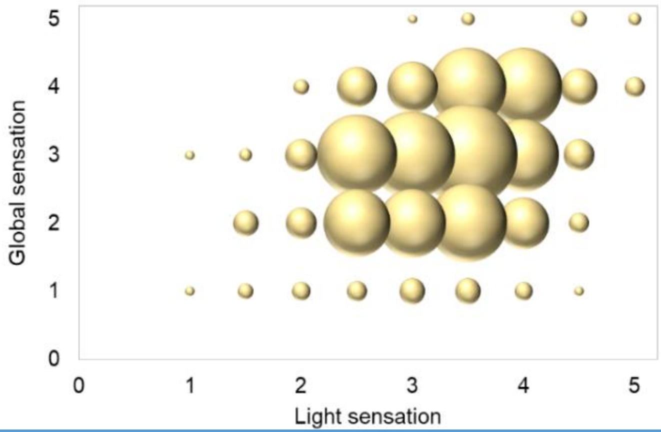
Average values of questionnaires results.

Classrooms	GLOBAL (Part A)	TH (Part B)	IAQ (Part C)	AC (Part D)	LT (Part E)
C1	3.33	3.28	3.21	3.46	3.47
C2	3.08	3.06	2.40	3.52	3.13
C3	2.77	2.78	2.89	2.88	3.12
C4	2.98	2.93	2.65	2.43	3.13
C5	2.12	2.05	1.82	3.05	3.29









Average values of questionnaires results.

Classrooms	GLOBAL (Part A)	TH (Part B)	IAQ (Part C)	AC (Part D)	LT (Part E)
C1	3.33	3.28	3.21	3.46	3.47
C2	3.08	3.06	2.40	3.52	3.13
C3	2.77	2.78	2.89	2.88	3.12
C4	2.98	2.93	2.65	2.43	3.13
C5	2.12	2.05	1.82	3.05	3.29

The multiple linear regression has been calculated using
GLOBAL as **independent variable**
TH, **IAQ**, **AC** and **LT** as **dependent variables**.

Multiple linear regression results.

	Coefficients	SD	t	p-value
(Costant)	-0.182	0.101	-1.809	
TH – Thermal environment	0.439	0.027	16.26	< 0.001
IAQ – Indoor Air quality	0.219	0.021	10.20	< 0.001
AC – Acoustics	0.228	0.029	7.97	< 0.001
LT – Lighting	0.161	0.031	5.27	0.002

After that the regression coefficients have been **normalized**.

Lighting (LT) 0.15
Acoustics (AC) 0.22
Thermal comfort (TH) 0.42
Indoor air quality (IAQ) 0.21

2. Analytic Hierarchy Process (AHP) from ranking list

Question within an overall evaluation questionnaires (object of an other research) in which it was asked to rank the four environmental factor from the most important to the less important.

2- In your opinion, to judge the comfortable school environment which aspect is most important?

Rank the four aspects from 1 (the most important) to 4 (the less important)

[ ] Air quality

[ ] Lighting

[ ] Acoustics

[ ] Thermal environment (temperature and relative humidity)

Sample: 458 students

Age: 25 years (SD=3.8 y)

Period: Sept. 2017 – Sept. 2018

2. Analytic Hierarchy Process (AHP) from ranking list

Post-processing of the results, filling the pairwise comparison matrix on the base of the ranking results

Explanation of pair wise comparison values

Scale	Degree of Preference	Explanation
1	Equal importance	Two criteria contribute equally to the objective
3	Moderate importance of one criteria over the other	Judgment slightly favours one criterion over the other.
5	Strong importance of one criteria over the other	Judgment strongly favours one criterion over the other.
7	Very strong importance of one criteria over the other	A criterion is favoured very strong over the other.
9	Extreme importance of one criteria over the other	Highest possible order of affirmation on the evidence that the preference is on one criterion over the other.
2,4,6,8	Intermediate values	When a value between two previous judgments is needed.

Pair wise comparison matrix

	IAQ	LT	AC	TH	Weights
IAQ	1	1/2	1/2	1/3	0.12
LT	2	1	2	1/2	0.27
AC	2	1/2	1	1/2	0.19
TH	3	2	2	1	0.42

Lighting (LT) 0.27
Acoustics (AC) 0.19
Thermal comfort (TH) 0.42
Indoor air quality (IAQ) 0.12

3. Analytic Hierarchy Process (AHP) from pair wise comparison

Indoor environmental quality in university classrooms

Among the parameters compared in each row, which the degree of importance for the indoor environmental quality in university classrooms?

Tick the box corresponding to the level of importance that you want to allocate between the two criteria.

9	7	5	3	1	3	5	7	9
Extremely strong	Very strong	Strong	Marginally strong	Equal	Marginally strong	Strong	Very strong	Extremely strong

	9	7	5	3	1	3	5	7	9	
Visual comfort (Lighting)										Acoustic comfort
Acoustic comfort										Indoor air quality
Indoor air quality										Thermal comfort
Thermal comfort										Visual comfort (Lighting)
Thermal comfort										Acoustic comfort
Visual comfort (Lighting)										Indoor air quality

Scale	Degree of Preference	Explanation
1	Equal importance	Two criteria contribute equally to the objective
3	Moderate importance of one criteria over the other	Judgment slightly favours one criterion over the other.
5	Strong importance of one criteria over the other	Judgment strongly favours one criterion over the other.
7	Very strong importance of one criteria over the other	A criterion is favoured very strong over the other.
9	Extreme importance of one criteria over the other	Highest possible order of affirmation on the evidence that the preference is on one criterion over the other.
2,4,6,8	Intermediate values	When a value between two previous judgments is needed.

Sample: 65 students

Age: 23.7 years (SD=2.8y)

Period: Sept. 2018 – Dec. 2018

3. Analytic Hierarchy Process (AHP) from pair wise comparison

	9	7	5	3	1	3	5	7	9	
Lighting - LT	0	3	5	9	31	11	6	0	0	**AC- Acoustics**
Acoustics - AC	0	2	17	12	9	9	7	7	2	**IAQ - Indoor air quality**
Indoor air quality - IAQ	0	1	5	3	15	24	14	3	0	**TH - Thermal comfort**
Thermal comfort - TH	0	7	11	11	10	17	7	2	0	**LT - Lighting**
Thermal comfort - TH	1	3	14	17	4	19	7	0	0	**AC - Acoustics**
Lighting - LT	0	3	13	19	4	12	8	3	3	**IAQ - Indoor air quality**

	←	=	→	
Lighting - LT	73	31	63	**AC- Acoustics**
Acoustics - AC	135	9	129	**IAQ - Indoor air quality**
Indoor air quality - IAQ	41	15	163	**TH - Thermal comfort**
Thermal comfort - TH	137	10	100	**LT - Lighting**
Thermal comfort - TH	151	4	92	**AC - Acoustics**
Lighting - LT	143	4	124	**IAQ - Indoor air quality**

Pair wise comparison matrix

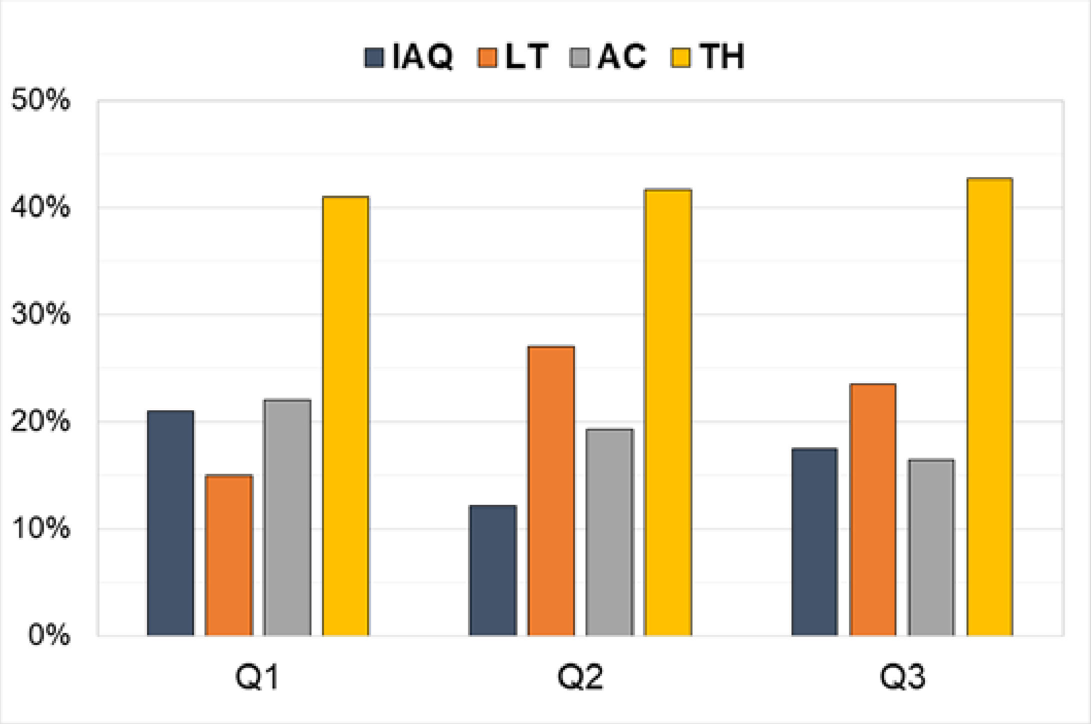
	IAQ	LT	AC	TH	Weights
IAQ	1	1	1	1/3	0.17
LT	1	1	2	1/2	0.23
AC	1	1/2	1	1/2	0.16
TH	3	2	2	1	0.43

Lighting (LT) 0.23
Acoustics (AC) 0.16
Thermal comfort (TH) 0.43
Indoor air quality (IAQ) 0.17

Research activity results

Weights obtained from the three subjective investigation

	Q1 REGRESSION	Q2 RANKING	Q3 PAIRWISE	AVERAGE VALUE
IAQ	0.21	0.12	0.17	**0.17**
LT	0.15	0.27	0.23	**0.22**
AC	0.22	0.19	0.16	**0.19**
TH	0.41	0.42	0.43	**0.42**



Weights for environmental factors in university classrooms (average values)

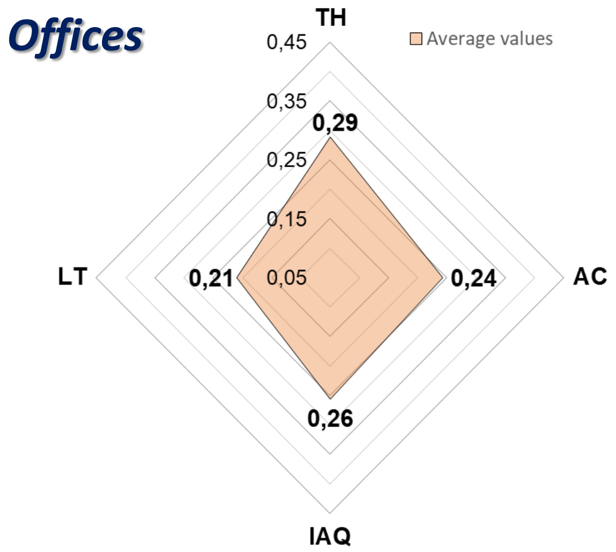
Lighting (LT) 0.22

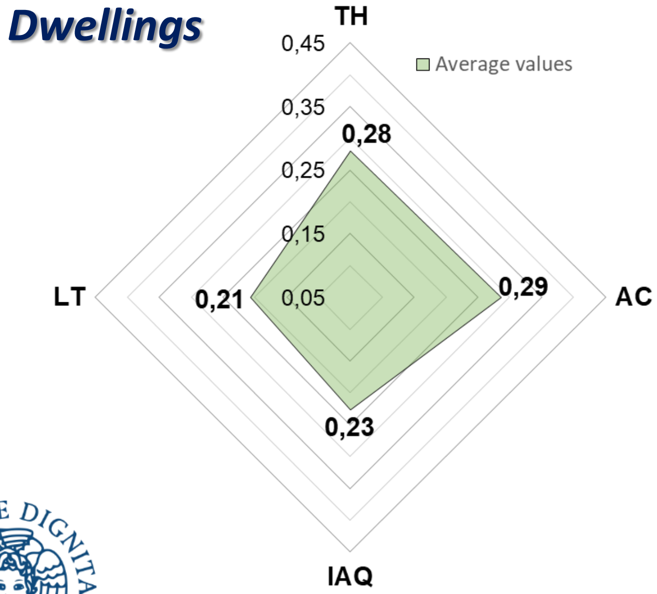
Acoustics (AC) 0.19

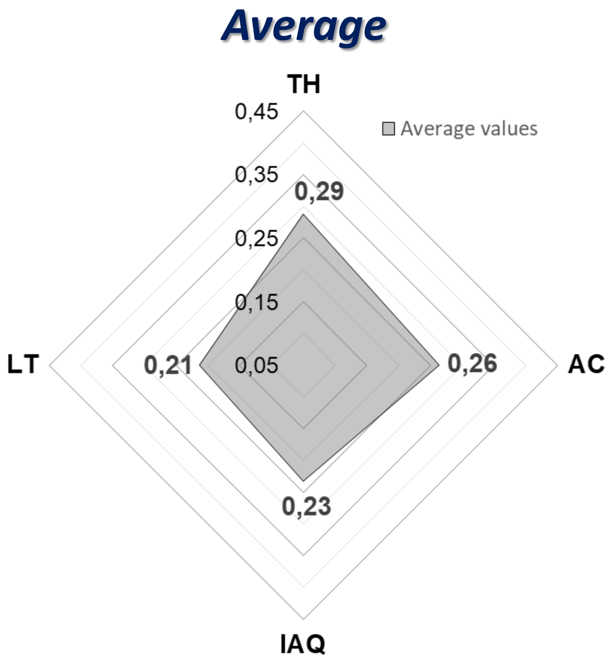
Thermal comfort (TH) 0.42

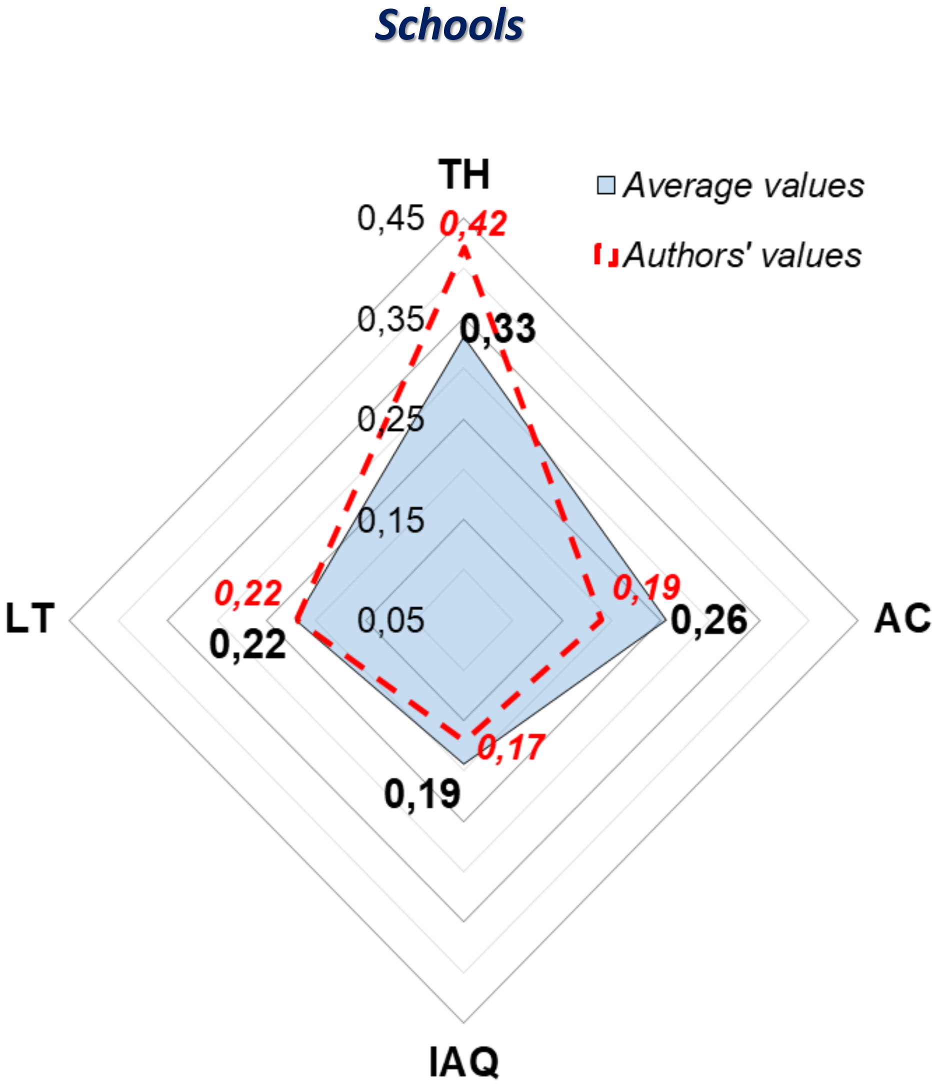
Indoor air quality (IAQ) 0.17

Final weighting factors









APPLICATION OF THE PROPOSED ASSESSMENT METHOD TO CASE STUDIES

CASE STUDIES

Whole Building

- ✓ University Hospital of Pisa
- ✓ School of Engineering of Pisa

Room

- ✓ Radiodiagnostic reporting rooms
- ✓ Sterilization unit
- ✓ University classrooms (IEQ)
- ✓ University classrooms (Lighting Quality)

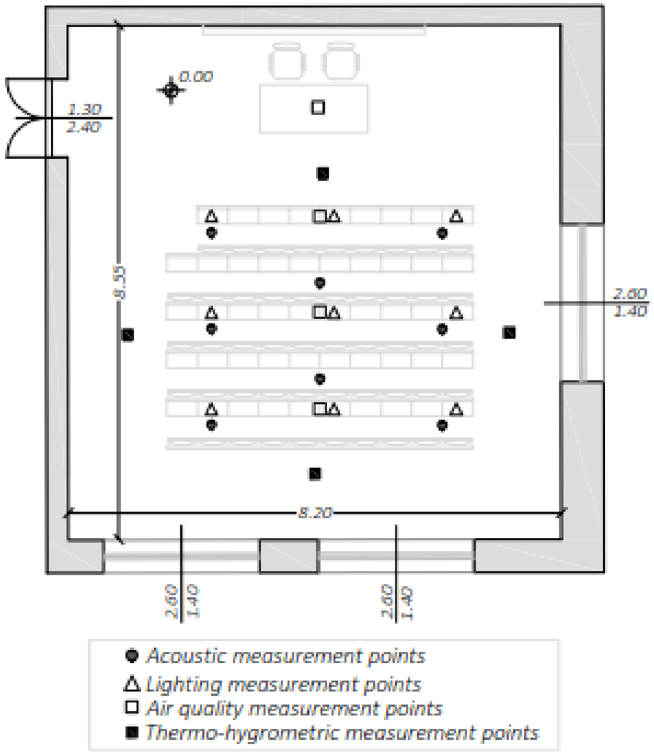
Single workstation

- ✓ Office workstation
- ✓ Radiodiagnostic reporting workstation
- ✓ Kit Control workstation (sterilization unit)

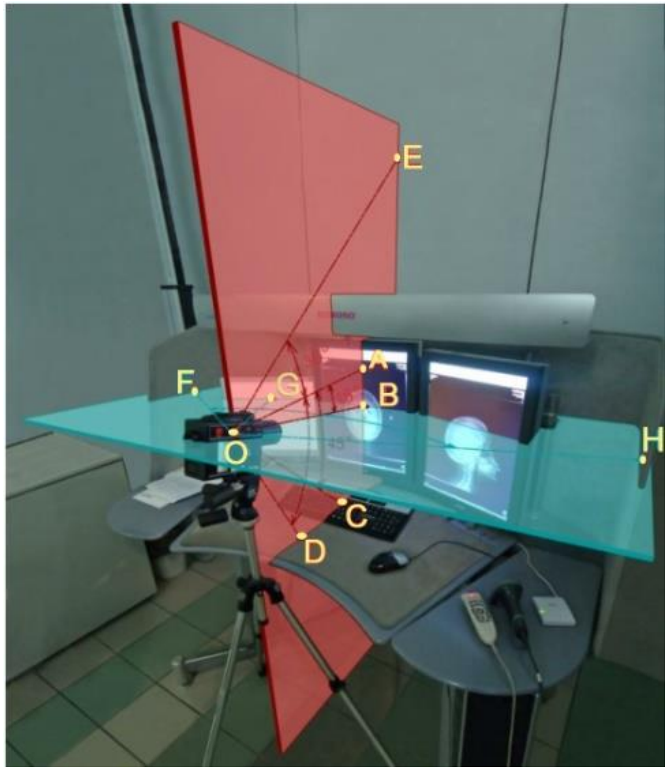
CASE STUDIES

Whole Building

Room



Single workstation



EXAMPLE OF THE OBTAINED RESULTS

The sterilization unit

Criteria	Sub-criteria	Indicator	P_B	P_R	DI	DI_{max}	DI_n	FS	Rank
Thermal environment	Temperature	T_{air} [°C]	20.0	22.0	0.00	1	0.00	0.000	-
	Humidity	RH [%]	40.0	25.4	0.37	1	0.37	0.053	3
Visual Environment	Luminance distribution	LR [-]	0.33	0.33	0.00	1	0.00	0.000	-
	Illuminance	E_m [lx]	1000	626	0.37	1	0.37	0.0041	4
Acoustical Environment	Sound Pressure Level – Direct field	SPL	70 dB 0.0632 Pa	73 dB 0.00893 Pa	0.41	1	0.41	0.054	2
	Sound Pressure Level – Diffuse field	SPL	65 dB 0.0356 Pa	71 dB 0.00710 Pa	1.00	1	1.00	0.129	1

P_B = Benchmark value

P_R = Real value

DI = Deviation Indicator

DI_n = Normalized deviation indicator

FS = Final Score

CONCLUSIVE REMARKS

Conclusive remarks

The proposed assessment method can be considered **flexible to different scales of observation** and **different types of buildings**.

Some aspects of the assessment method can still be improved, especially with regard to the robustness of the **weighting schemes** and the **Deviation Indicators** which could be better adapted to the various indicators used from time to time.

In any case, the general character of **the proposed method** allows it to be **easily modified** without losing its characteristics.

Published Papers

1. Leccese F., Salvadori G., Rocca M., Buratti C., Belloni E. *A method to assess lighting quality in education rooms using analytic hierarchy process*. ***Building and Environment* 2020**, 168, Nr. 106501. DOI: 10,1016/j.buildenv.2019.106501.

2. Fantozzi, F.,Hamdi H., Rocca M., Vegnuti, S. *Use of automated control systems and advanced energy simulations in the design of climate responsive educational building for Mediterranean area*. ***Sustainability* 2019**, 11(6), art. nr. 1660. DOI: 10.3390/su11061660.

3. Fantozzi F., Rocca M., Spinelli N. *Assessment of Reverberation Times in University Classroom: Comparison between Analytic Formulae, Software Simulations and Measurements*. ***International Congress Building Simulation* 2019**, Rome, September 2-4, 2019.

4. Leccese F., Rocca M., Salvadori G. *Fast estimation of Speech Transmission Index using the Reverberation Time: Comparison between predictive equations for educational rooms of different sizes*. ***Applied Acoustics* 2018**, Vol. 140, pp. 143-149. DOI: 10.1016/j.apacoust.2018.05.019.

5. Rocca M. *Human response to the indoor environment. A collection of literature models.* ***18th International Conference on Environment and Electrical Engineering (EEEIC)*** (EEEIC/I&CPS Europe), Palermo, June 12-15, **2018**, pp. 284-289.

6. Burattini C., Gugliermetti L. Fantozzi F., Rocca M. *Simplified assessment of blue light emissions based on photometric measurements. Example of application to LEDs and fluorescent lamps for general lighting systems.* ***18th International Conference on Environment and Electrical Engineering (EEEIC)*** (EEEIC/I&CPS Europe), Palermo, June 12-15, **2018**, pp. 2245-2249.

Published Papers

7. Rocca M. *Health and well-being in indoor work environments: A review of literature.* ***17th IEEE International Conference on Environment and Electrical Engineering*** (EEEIC/I and CPS Europe), Milan, June 6-9, **2017**, art. nr. 7977516. DOI: 10.1109/EEEIC.2017.7977516.

8. Fantozzi F., Leccese F., Rocca M., Salvadori G. *Risk assessment arising from exposure to artificial optical radiation: Results of an extensive evaluation campaign in the hospitals of Tuscany (Italy).* ***17th IEEE International Conference on Environment and Electrical Engineering*** (EEEIC/I and CPS Europe), Milan, June 6-9, **2017**, art. nr. 7977447. DOI: 10.1109/EEEIC.2017.7977447.

9. Fantozzi F., Le Bail L., Leccese F., Rocca M., Salvadori G. *General lighting in offices building: Techno-economic considerations on the fluorescent tubes replacement with LED tubes*. ***International Journal of Engineering and Technology Innovation* 2017**, 7 (3), pp. 143-156.

10. Leccese F., Salvadori G., Montagnani C., Ciconi A., Rocca, M. *Lighting assessment of ergonomic workstation for radio diagnostic reporting.* ***International Journal of Industrial Ergonomics* 2017**, 57, pp. 42-54. DOI: 10.1016/j.ergon.2016.11.005.

11. Testi D., Rocca, M., Menchetti, E., Comelato, S*. Criticalities in the NZEB retrofit of scholastic buildings: Analysis of a secondary school in Centre Italy.* ***Energy Procedia* 2017**, 140, pp. 252-264. DOI: 10.1016/j.egypro.2017.11.140.

12. Leccese F., Salvadori G., Rocca M. *Critical analysis of the energy performance indicators for road lighting systems in historical towns of central Italy.* ***Energy* 2017**, 138, pp. 616-628. DOI: 10.1016/j.energy.2017.07.093.

Courses and seminars attended (in chronological order)

1. *Conference:* **BS2019: 16th IBPSA International Conference and Exhibition.** Rome 2-4 September 2019.
2. Course: “**Insegnare a Insegnare**” (60 hrs), November 2018 – June 2019.
3. Course **“Fundamentals of multi-objective optimization”** (20 hrs), October – November 2018.
4. *Conference:* **73th ATI National Congress**. Pisa 12-14 September 2018.
5. *Course* “**Academic English – level C1+**” Prof. Joanne Spataro (30 hrs), April - July 2018.
6. *Conference:* **18th IEEE International Conference on Environmental and Electrical Engineering and 2nd Industrial and Commercial Power Systems Europe**. Palermo 12-15 June 2018.
7. *Course:* “**Introduction to Technical Communication**” Prof. Sameer Khandenkar (9 hrs), May-June 2018.
8. *Seminar:* IEEE Xplore Digital Library training “**How to write a basic technical paper?**” Pisa, 19th April 2018.
9. *Seminar:* “**Prodotti della ricerca: diffusione e valorizzazione**” Valorizzare l’esperienza del Dottorato di ricerca, a cura dell’Ufficio ricerca dell’Università di Pisa, 12th April 2018.
10. *Course:* **PhD+ 2018 Research valorization, innovation, entrepreneurial mindset** (26 hrs), February-March 2018.
11. *Conference:* REHVA Brussels Summit – REHVA Conference on “**Delivering healthy and energy efficient buildings with EPBD**”. 14th November 2017.
12. *Conference:* **17th IEEE International Conference on Environmental and Electrical Engineering and 1nd Industrial and Commercial Power Systems Europe**. Milan 6-9June 2017.
13. *Conference:* **50th AiCARR international Conference: Beyond the NZEB.** Matera 10-11 May 2017.
14. *Course:* “**Elementi di statistica**” Prof. Franco Flandoli (9 hrs), May-June 2018.
15. *Seminar:* “**Una strategia energetica nazionale per il raggiungimento degli obiettivi europei 2030”**. Scuola di Ingegneria, 16th Mach 2017.
16. *Course* “**Academic English – level C1**” Prof. Joanne Spataro (30 hrs), January - March 2017.
17. *Seminar:* “**Horizon 2020: il Bando Incentivi di Ateneo e le opportunità 2017**”. Polo Carmignani, 25th January 2017.

PROPOSAL OF THESIS REVIEWERS

1. Associate Professor **Cinzia Buratti**
University of Perugia, Dept. of Engineering
e-mail: cinzia.buratti@unipg.it
Phone nr. +39 075 585 3693

2. Associate Professor **Boris Igor Palella**
Naples University Federico II, Dept. of Industrial Engineering
e-mail: borisigor.palella@unina.it
Phone nr. +39 081 7682618

Thank you for your kind attention