technologies

MDPI

Technical Note

Deriving an Indoor Environmental Index for Portuguese Office Buildings

João F. P. Gomes [1,2,*] and Hélder M. S. Esteves [2]

1 Chemical Engineering Department, ISEL—Instituto Superior de Engenharia de Lisboa, Lisbon Polytechnic, R. Conselheiro Emídio Navarro, 1959-007 Lisboa, Portugal
2 CERENA—Centro de Recursos Naturais e Ambiente, IST—Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal; heldersalvacao@sapo.pt
* Correspondence: jgomes@deq.isel.ipl.pt; Tel.: +351-21-8317066; Fax: +351-21-8317267

Academic Editor: Manoj Gupta
Received: 31 October 2016; Accepted: 14 December 2016; Published: 16 December 2016

Abstract: In 2002, the European Commission (EU) issued a Directive aiming to reduce the energy consumption of buildings, which was adopted by the EU member states and came into force in 2006. Portugal adopted it by issuing law decrees in 2006 which considered not only the energy saving aspects but also additional specific measures aiming to protect indoor air quality (IAQ). This new legislation is now being enforced, and it will be necessary to define compliance acceptance levels for the prescribed indoor air limits. The use of comfort or environmental indexes could be of considerable help to ameliorate the evaluation of IAQ. This paper presents a proposal of an index regarding IAQ which considers both the aspects of thermal comfort and non-toxicity. The proposed index was calculated for offices of several European countries, available from previous studies and for Portugal as well. Bearing in mind there is few existing data, this study is consistent with the proposed index, as the obtained values are similar to Greece, which has several similarities with the Portuguese situation.

Keywords: indoor air quality; environment; index; office buildings; energy

1. Introduction

In 2002, the European Commission issued a Directive [1] aiming to reduce the energy consumption in buildings, bearing in mind that buildings are responsible for 20%–30% of energy consumptions in the European Union. This Directive intends to specify minimum energetic performance requirements for new buildings, as well as for existing buildings having an area larger than 1000 m^2, and aims to put into practice an energy consumption labelling scheme for buildings. The member states of the European Union adopted this Directive which came into force in 2006.

Since the early 1990s, Portugal has had national legislation issuing orientations for building construction and operation (mainly regarding insulation of walls, location to maximize solar exposition, as well as performance requirements for air conditioning systems) [2,3], intending to decrease energy consumption in buildings.

Therefore, Portugal adopted the 2002 European Directive by issuing law decrees in 2006 [4–6], which considers not only the energy saving aspects, but also additional specific measures aiming to protect indoor air quality (IAQ) in accordance to the approach proposed by the EN standard 15251 [7]. Although the reduction of energy consumption in buildings can result in lower ventilation rates and, thus, in lower IAQ, it should be noted that the European Directive of 2002 did not have any imposition, on member states, regarding IAQ. Portugal is one of the few member states of the European Union to issue air quality standards for buildings that are presented in Table 1.

Table 1. Indoor air pollutant limit values per Portuguese regulations.

Indoor Air Pollutant	Demarcation Value (*)
PM_{10}	0.15 mg/m^3
CO_2	1800 mg/m^3
CO	12.5 mg/m^3
O_3	0.2 mg/m^3
HCHO	0.1 mg/m^3
TVOC	0.6 mg/m^3
Bacteria	500 CFU/m^3
Fungi	500 CFU/m^3
Radon	400 Bq/m^3

(*) Note: Demarcation values represent standards, guidelines, and suggestions of pollutant levels associated with health effects.

Nowadays, the Portuguese government is trying to enforce this new legislation and issued specific regulations regarding the auditing and evaluation scheme of IAQ. Therefore, it will be necessary to define compliance acceptance levels regarding the prescribed indoor air limits. The use of comfort or environmental indexes could be of considerable help in order to ameliorate the evaluation of IAQ, as reviewed by de Gennaro et al. [8] and Tham [9].

It should be noted that the European Directive of 2002 considers the labelling of buildings in terms of energy consumption. Likewise, the Portuguese regulations to be issued could prescribe the use of a similar labelling system for buildings regarding IAQ.

In fact, several efforts have been made to formulate a global measure of indoor air pollution [10,11]. Such a metric is distinct from a measure of several individual indoor pollutants and should be associated with symptoms of those exposed to indoor air pollution. More than that, it must satisfy three basic requirements as pointed out by Moschandreas and Sofoglu [12]:

(i) it must be understood easily by all involved in assessing the environment, comprising the consumer, the potential polluter, the evaluator, and the regulator;
(ii) it must associate well with measurements of impact caused by the contamination ranked by the metric;
(iii) it must enable those concerned to manage the environment efficiently.

Environmental quality indices do not constitute a new tool of inquiry and have been developed and used for ambient air [13,14] and water quality [15,16]. Some indices have been proposed such as the Indoor Air Pollution Index (IAPI) [17], the Indoor Discomfort Index (IDI) [10], and the Indoor Environmental Index (IEI) [10].

2. Methodology

2.1. Previously Developed Indexes

2.1.1. IEI—The Indoor Environmental Index

The IEI [12] is an index that meets the above-mentioned criteria and includes the IAPI and the IDI indices, which considers IAQ as maintaining the air pollutant concentration lower than the toxicity levels and the thermal comfort conditions in terms of indoor temperature and relative humidity. The IEI is defined as the arithmetic mean of both these two indices, which is expressed as follows:

$$\text{IEI} = (\text{IAPI} + \text{IDI})/2. \tag{1}$$

2.1.2. IAPI—Indoor Air Pollution Index

The IAPI [17] is an index that includes eight pollutants prescribed in indoor air regulations: bacteria, CO, CO_2, HCHO, fungi, $PM_{2.5}$, PM_{10}, and Total Volatile Organic Compounds (TVOCs).The index aggregates sub-indexes using arithmetic means in conjunction of a tree-structured calculation method, as shown elsewhere [12].

IAPI is calculated using the following equation:

$$IAPI = (1/I) \sum_I (1/J) \sum_j (1/K) \sum_k 10 \left(1 - [(C_{i,j,k}^{max} - C_{i,j,k}^{obs})/(C_{i,j,k}^{max} - C_{i,j,k}^{min})] \times [(C_{i,j,k}^{dmc} - C_{i,j,k}^{obs})/(C_{i,j,k}^{dmc})]\right) \quad (2)$$

for $C^{max} > C^{obs}$ and $C^{dmc} > C^{obs} > C^{min}$, where I is the number of level −3 groups, I = 2; J is the number of level −2 groups in each level −3 group, J = 2; K is the number of level −1 pollutant variables in each level −2 group, K = 2; C^{max} is the maximum measured concentration; C^{min} is the minimum measured concentration; C^{dmc} is the demarcation concentration; C^{obs} is the measured concentration in the subject building.

Being defined as such, this index requires a set of several previously measured concentrations regarding these pollutants in a significant number of buildings, which means that, for each referred pollutant, a pair of values of C^{max}/C^{min} must be selected from a database of values. Apart from that, other concentrations have to be available, such as a demarcation concentration, which is a limit value established by a standard or guideline, and measured concentrations in the subject building.

The index is a unitless number between 0 (lowest pollution level or best IAQ) and 10 (highest pollution level or worst IAQ). Constraints for calculation of the IAPI index include the following:

(a) $C^{obs} = C^{max}$ and $C^{obs} = C^{dmc}$, when $C^{max} < C^{obs}$;
(b) $C^{obs} = C^{dmc}$, when $C^{dmc} < C^{obs}$ but $C^{obs} < C^{max}$;
(c) $C^{obs} = C^{min}$, when $C^{obs} < C^{min}$.

2.1.3. IDI—Indoor Discomfort Index

The IDI [12] is estimated using temperature (T) and relative humidity (RH) as given by Equation (3):

$$IDI = (1/L) \sum_i 10 \, |CA_{i,opt} - CA_{i,obs}| / (CA_{i,ucl} - CA_{i,lcl}) \quad (3)$$

for 25 > CA_{obs} > 65 for RH; and 28 > CA_{obs} >16 for T; CA is the comfort agent, L = 2; CA_{opt} is the optimum comfort agent value, T_{opt} = 22 °C, RH_{opt} = 45%, CA_{ucl} is the upper comfort level, T_{ucl} = 25 °C, RH_{ucl} = 55%, CA_{lcl} is the lower comfort level, T_{lcl} = 19 °C, RH_{lcl} = 35%, and CA_{obs} is the measured comfort agent in the subject building.

Thus, the absolute difference of the observed value to the defined optimum value (22 °C for temperature and 45% for relative humidity (RH)) relative to the present comfort range (3 °C for temperature and 10% for RH either way from the optimum value) is used to estimate the IDI. Again, the index is a unitless number ranging from 0 to 10. As defined previously regarding the IAPI, a high index value indicates a high level of discomfort; a low index value denotes a low level of discomfort. Constraints for calculation of the IDI are as follows:

(a) $CA_{RH,obs}$ = 65, when $CA_{RH,obs}$ > 65;
(b) $CA_{RH,obs}$ = 25, when $CA_{RH,obs}$ < 25;
(c) $CA_{T,obs}$ = 28, when $CA_{T,obs}$ > 28;
(d) $CA_{T,obs}$ = 16, when $CA_{T,obs}$ < 16.

2.2. Proposal of an Index for Portuguese Office Buildings (pIAPI)

Bearing in mind the specific features of the Portuguese regulations regarding IAQ, as presented in Table 1, a new IAPI definition (pIAPI) is needed in order to include this particular situation. In this case, J = 2 and K = 2, as defined in the original index.

However, in what concerns I, the situation is slightly different from the previous one, as the regulations include three inorganic gases (CO, CO_2, and O_3) and only one class of particulate matter (PM_{10}). Nevertheless, this definition incoherence can be logically surpassed if we consider the average value of I = 2, which means that it will include the three inorganic gases as well as PM_{10} regarding particulate matter.

The actual regulations also include a demarcation value for radon. In the new proposed index, this parameter is disregarded, as radon concentrations do not relate with the short term, reversible symptoms on human health of building occupants.

Another situation arises that makes it necessary to consider the definition of a new index, as in the Portuguese situation, values of C^{max} and C^{min}, for each pollutant are not available yet. In fact, bearing in mind that the Portuguese regulation is recent and is only now being enforced, a minimum of 3–5 years is to be expected before there is enough data on Portuguese office buildings that is organized in a systematic way so that these values can be derived. Therefore, for the time being, the IAPI index should be considerably simplified from its original definition so that it can be applied to this situation. It seems reasonable to consider that C^{max} does not exceed the demarcation values presented in Table 1, but can reach it by 95%. Regarding C^{min}, it also seems reasonable to take a value of 1%, which is lower than the demarcation value. Therefore, if we take

$$C^{max} = 0.95C^{dmc} \tag{4}$$

$$C^{min} = 0.01C^{dmc} \tag{5}$$

into Equation (2) and rearrange them, we obtain

$$pIAPI = (1/I)\sum_i (1/J) \sum_j (1/K) \sum_k 10 \,(1 - [(0.95\, C_{i,j,k}{}^{dmc} - C_{i,j,k}{}^{obs})/(0.94\, C_{i,j,k}{}^{dmc}\,) \times [(C_{i,j,k}{}^{dmc} - C_{i,j,k}{}^{obs})/(C_{i,j,k}{}^{dmc})]). \tag{6}$$

The IDI is still given by Equation (3), whereas the global IEI is given by Equation (1).

3. Results and Discussion

A previous European project [18] constituted an exhaustive study of auditing the IAQ in 56 European office buildings. During this study, physical and chemical measurements were made in the space of those office buildings, resulting in a systematic evaluation of the indoor concentrations of pollutants such as carbon dioxide (CO_2), carbon monoxide (CO), total volatile organic compounds (TVOCs), particulate matter (PM_{10}), as well as the thermal parameters operative temperature and relative humidity. The main characteristics of the selected buildings are presented in Table 2.

For these office buildings, the determination of the most significant indoor air pollutants (CO, CO_2, particulate matter, and total volatile organic compounds) was performed. The reported average concentrations found in buildings per country are presented in Table 3. Moreover, the air temperature and relative humidity were measured and the average values per country are presented in Table 4.

The average indoor level for CO_2 ranges from 516 to 778 ppm, with a mean level of 673 ± 60 ppm, and no evidence of geographic differences were found along the north–south or east–west axes or between maritime and more continental settings. The average indoor CO level was below 1 ppm. The particulate matter values were log-normally distributed, with a geometric mean of 66 μg/m^3, a large geometric standard deviation of 2.7 and a median at 62 μg/m^3. In general, the particulate concentration remained below 120 μg/m^3, except for several buildings in Greece (GR) and Switzerland (CH). The average TVOCs per building were log-normally distributed. The average TVOC per building in the investigated rooms ranged from 118 to 528 μg/m^3, with a median of 162, a geometric mean of 172, and a geometric standard deviation of 2.1. The mean air temperatures measured in the buildings per country were, in general, in the upper limit of the recommended values given in the thermal comfort standard ISO/CEN 7730 for the winter (20–24 °C).

Table 2. Summary of the main characteristics of 56 selected buildings [18].

Characteristics		Percentage (%)
Situation	Countryside	14
	Suburbs	25
	Downtown	54
	Industrial area	7
Total floor area	<2500 m^2	16
	2500–7500 m^2	30
	7500–15,000 m^2	29
	>15,000 m^2	25
Number of occupants	<200	36
	200–500	34
	500–1000	16
	>1000	14
Age	2–5 years	29
	5–10 years	21
	10–20 years	11
	>20 years	39
Number of floors	1–3	21
	3–7	48
	7–10	13
	>10	18
Smoking	Yes	59
	Certain areas	23
	No	18

Table 3. Average CO_2, CO, particulate matter, and TVOC concentrations measured in buildings in each country [18].

	NL	DK	UK	GR	FR	CH	SF	N	D
CO_2 (ppm)	656	736	516	587	778	744	737	628	674
CO (ppm)	0.5	0.6	0.7	0.9	1.9	<1.0	0.8	1.4	0.7
Particulate matter (μg/m^3)	72	88	20	149	76	181	51	20	61
TVOC (μg/m^3)	179	135	436	495	413	518	118	528	146

Note: CH = Switzerland; D = Germany; DK = Denmark; FR = France; GR = Greece; N = Norway; NL = Netherlands; SF = Finland; UK = United Kingdom.

Table 4. Average results of the thermal measurements in each country [18].

	NL	DK	UK	GR	FR	CH	SF	N	D
Air temp. (°C)	22.3	23.7	22.9	23.5	23.5	22.9	22.3	23.4	21.7
Relative humidity (%)	31	29	36	33	44	39	19	17	41

The Nordic countries (Denmark (DK), Finland (SF), and Norway (N)) had a relative indoor humidity below 30%, which is not uncommon in these countries, whereas the highest relative indoor humidity values were found in France (FR) and Germany (D).

In this project, the perceived air qualities in the investigated buildings were also evaluated by trained panels, expressed in decipol [18]. The mean perceived air quality for all 56 European audited buildings was about 6 decipol, which corresponds to roughly 50% dissatisfied visitors.

Using this data, the air quality indexes pIAPI, IDI, and IEI were calculated for the "average" building per country, using the previously described Equations (1)–(3), and the obtained values are presented in Table 5.

Table 5. Calculated indoor air quality (IAQ) indexes for 56 European office buildings averaged per country.

	NL	DK	UK	GR	FR	CH	SF	N	D
pIAPI	2.459	2.642	2.296	2.955	4.489	4.153	2.387	3.306	2.437
IDI	3.750	5.250	3.167	4.250	0.333	2.000	6.833	8.333	1.000
IEI	3.105	3.946	2.731	3.603	2.411	3.076	4.610	5.820	1.719

The newly proposed index for the Portuguese situation results in the following: IAPI = 3.559; IDI = 4.250; IEI = 3.094. It should be noted that the calculated IEI index closely compares with the IEI index in Table 5 for Greece (GR), which (among the referred countries) has more similarities with Portugal in terms of office construction, climate, and cultural habits. This is a good indication about this index, although it still requires further validation from actual measurements that are to be done, in future, in Portuguese office buildings.

As a preliminary study, this methodology was applied to a set of measurements performed on university office buildings located in downtown Lisbon [19] presented in Table 6.

Table 6. CO_2, CO, particulate matter, and TVOC concentrations, and found in university buildings in downtown Lisbon, Portugal, together with air temperature and relative humidity [19].

	1	2	3	4	5	6	Average
CO_2 (ppm)	743	392	470	1089	654	326	612
CO (ppm)	0	0	0	0	0	0	0
Particulate matter (μg/m^3)	66	0	133	12	158	192	93.5
TVOC (μg/m^3)	200	0	0	60	120	0	63
Air temp. (°C)	26	23	24	27	26	25	25.2
Relative humidity (%)	59	64	48	43	40	42	49.3

Considering these measurements, the air pollution indexes were calculated as before, and are presented in Table 7.

Table 7. Calculated IAQ indexes for university buildings in downtown Lisbon.

	1	2	3	4	5	6	Average
pIAPI	2.774	0.8113	2.179	1.597	2.840	1.840	2.442
IDI	6.833	5.583	2.417	4.667	4.583	3.25	3.742
IEI	4.804	3.197	2.298	3.131	3.712	2.545	3.092

It can be easily observed that the calculated individual indexes (for each university building) somewhat differ from the average value calculated as IEI = 3.094, as referred previously. Although the average indexes in this case are only based on 6 observations, IEI = 3.092 is in clear accordance with the postulated mean index for Portugal of IEI = 3.094. Nevertheless, further measurements are still needed for this task, considering that the available data is somewhat limited.

4. Conclusions

The proposed index, based on previously developed indexes for other regulated situations and validated with actual measurements done in other European countries, is intended to adapt to the current Portuguese situation, which is currently being implemented as a result of legislation. The use of this index can now be evaluated using observed concentrations in actual office environments that are to be done in the future. This methodology will help to improve the current developed index and to obtain a set of values that can be used in the future as reference values. Therefore, this methodology can be improved and developed further, if necessary. Preliminary data validate the proposed methodology, although this validation is based on a limited number of cases.

Author Contributions: João F. P. Gomes conceived and design the study. Hélder M. S. Esteves performed the calculations. Both authors were involved in the analysis of data, the discussion of results and the writing of the paper. All authors have read and approved the final manuscript.

Conflicts of Interest: Both authors declare no conflict of interest in this paper.

References

1. EC, European Directive 2002/91/CE, 16/12/2002 (European Directive). Available online: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32002L0091 (accessed on 15 December 2016).
2. DL No. 40/90, DR I, 6/2/1990 (Portuguese Decree). Available online: https://dre.pt/application/file/334688 (accessed on 15 December 2016).
3. DL No. 156/92, DR I, 29/7/1992 (Portuguese Decree). Available online: https://dre.pt/application/file/275291 (accessed on 15 December 2016).
4. DL No. 78/2006, DR I, 4/4/2006 (Portuguese Decree). Available online: https://dre.pt/application/file/672552 (accessed on 15 December 2016).
5. DL No. 79/2006, DR I, 4/4/2006 (Portuguese Decree). Available online: https://dre.pt/application/file/672553 (accessed on 15 December 2016).
6. DL No. 80/2006, DR I, 4/4/2006 (Portuguese Decree). Available online: https://dre.pt/application/file/672550 (accessed on 15 December 2016).
7. European Standard. *Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics*; EN 15251:2007; CEN: Brussels, Belgium, 2007.
8. De Gennaro, G.; Dambruoso, P.; Loiotile, A.; Di Gilio, A.; Giungato, P.; Tutino, M.; Marzocca, A.; Mazzone, A.; Palmisani, J.; Porcelli, F. Indoor air quality in schools. *Environ. Chem. Lett.* **2014**, *12*, 467–482. [CrossRef]
9. Tham, K. Indoor air quality and its effects on humans—-A review of challenges and developments in the last 30 years. *Energy Build.* **2016**, *130*, 637–650. [CrossRef]
10. Sofuoglu, S.; Moschandreas, D. The Link between Symptoms of Office Building Occupants and In-Office Air Pollution. The Indoor Air Pollution Index. *Indoor Air* **2003**, *13*, 332–343. [CrossRef] [PubMed]
11. Sekhar, S.; Tham, K.; Cheong, D.; Wong, N. A Study of Indoor Air Pollutant Standard Index (IPSI) and Building Symptom Index (BSI). In Proceedings of the Healthy Buildings, Espoo, Finland, 6–10 August 2000; Volume 1, pp. 145–150.
12. Moschandreas, D.; Sofuoglu, S. The Indoor Environmental Index and Its Relationship with Symptoms of Office Building Occupants. *J. Air Waste Manag. Assoc.* **2004**, *54*, 1440–1451. [CrossRef] [PubMed]
13. MURC. MURC Index Tells Detroiters How Dirty Air Is. *Air Eng.* **1998**, *10*, 28.
14. Green, M. An Air Pollution Index Based on Sulfur Dioxide and Smoke Shade. *J. Air Pollut. Control Assoc.* **1966**, *11*, 703–706. [CrossRef]
15. Horton, R. An Index Number Ratying System for Rating Water Quality. *J. Water Pollut. Control Fed.* **1965**, *37*, 300–306.
16. Brown, R.; McClelland, N.; Deinninger, R.; Tozer, R. Water Quality Index—Do we dare? *Water Sew. Works* **1970**, *117*, 339–343.
17. Moschandreas, D.; Sofuoglu, S. The Indoor Air Pollution. In Proceedings of the Indoor Air, Edinburgh, UK, 9–13 August 1999; Volume 2, pp. 261–266.
18. Bluyssen, P.M.; De Oliveira Fernandes, E.; Groes, L.; Clausen, G.; Fanger, P.O.; Valbjørn, O.; Bernhard, C.A.; Roulet, C.A. European Indoor Air Quality Audit Project in 56 Office Buildings. *Indoor Air* **1996**, *6*, 221–238. [CrossRef]
19. Gomes, J.E.P.; Bordado, J.C.M.; Sarmento, G.; Dias, J. Measurements of indoor air pollutant levels in a university office building. *J. Green Build.* **2007**, *2*, 123–129. [CrossRef]