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Towards a holistic approach to indoor environmental quality assessment: Weighting schemes to combine effects of multiple environmental factors

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A R T I C L E I N F O

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A B S T R A C T

In the recent past, great attention has been posed on the assessment of the energy performance and of the operating and maintenance costs of the building stock. Currently, new approaches of analysis are considered by the scientific community, which put the occupant's well–being at the centre of the evaluation process. In this context, the IEQ assessment acquires an ever increasing importance, especially if the combined effects of multiple environmental factors are considered. With this purpose, to date, different weighting schemes can be found in the literature, obtained through subjective investigations and mathematical methods. In this paper, the weighting schemes proposed in the literature in the period 2002–2018 were examined, considering the survey methodologies used. The more relevant studies found in the literature were compared and the related weighting schemes were discussed, based on the intended use of the buildings. In particular, 122,000 questionnaires in 18 different countries all over the world were examined and the most relevant environmental factors were selected: Thermal Environment (TH), Air Quality (AQ), Acoustics (AC), and Lighting (LT). Three different average weighting schemes were obtained for each of the following uses: offices, schools, dwellings; a final additional weighting scheme was obtained considering the average values of the normalized weights for all the building uses, a possible solution for buildings with an unspecified or not unique intended use. Moreover, an original weighting scheme was obtained and proposed on the basis of the results of three different subjective surveys, involving about 1400 participants, carried out in some university classrooms at the School of Engineering of the University of Pisa: it was compared with the one obtained by the literature for school buildings. It was observed an overestimation of the importance of TH (0.42 instead of 0.33) and an underestimation of AC (0.19 instead of 0.26), whereas AQ and LT are in accordance (0.17 instead of 0.19 and 0.22, respectively). The results of the present study can be useful to those who intend to deal with holistic approaches to building design, for which accurate assessments of occupants' well-being are taken into consideration as well as aspects related to energy performance and building management costs.

1. Introduction

The Indoor Environmental Quality (IEQ) is recognized to be a key factor in buildings design and construction, as internal conditions significantly impact on well–being, productivity, health, and safety of occupants [1,2]. The concept of IEQ is very broad and depends on many aspects, generally grouped into four main environmental factors: thermal environment, air quality, acoustics, and lighting [3–6]. In the recent past, great attention has been posed on the assessment of the energy performance [7,8] and of the operating and maintenance costs [9,10] of the building stock. Currently, new approaches of analysis are considered by the scientific community, which put occupants well–being at the centre of the evaluation process and reconsider occupants and buildings interactions, increasing the complexity level of the analysis methods and tools [11]. According to these approaches, energy and financial evaluations are accompanied by evaluations on occupant's comfort, health, safety, some of which based on subjective perceptions [12]. In this context, the IEQ assessments acquire an ever increasing importance, especially when the combined effects of multiple environmental factors are considered [3,13]. Unfortunately, to date there are no standardized methodologies for the IEQ assessment [14], whereas specific indications are available on

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the assessment of individual environmental factors [15–18]. These assessments are mainly performed on the basis of subjective surveys (by way of the administration of questionnaires) and often they are integrated by objective surveys (by way of in situ measurements) [13].

Different proposals of IEQ assessment methods are present in the scientific literature. In order to take into account the combined effects of various environmental factors, different weighting schemes are defined, depending on the importance assigned to each of them towards overall comfort [19]. As it is easy to understand, the choice of the weighting scheme used in the evaluation is of decisive importance and it can affect the results of the entire evaluation process, so extreme caution and great knowledge are necessary to make this choice. Moreover, there is still no consolidated position in the scientific literature on which a weighting scheme should be used, when considering the different environmental factors and the intended use of the building. It seems therefore appropriate to focus more studies on this topic, in order to push knowledge forward [20].

In this framework the present study has two main aims: i) to properly collect information on the weighting schemes so far present in the international scientific literature and ii) to propose an original weighting scheme. The scientific literature was examined considering the used survey methodologies, both in terms of subjective investigations and of collected data analysis. Furthermore, the more relevant studies found in the literature were compared and the related weighting schemes were discussed in relation to the intended use of the building. An original weighting scheme was obtained and proposed on the basis of the results of three different subjective surveys, involving about 1400 participants, carried out in university classrooms at the School of Engineering of Pisa. The obtained weighting scheme was compared with the other ones found in the literature, specifically devoted to school buildings. The results of the present study represent an attempt to extend the research on the issue of the reliability of weighting schemes of environmental factors, for specific categories of buildings.

2. Literature review

In order to check which weighting schemes are present in the scientific literature to date, which ones are the most used, for which uses of the buildings they were developed, and with which methods (analytical or experimental) they have been determined, careful literature search was carried out. The literature search was conducted by using four of the largest scientific databases, i.e. *Google Scholar, ScienceDirect*, *Scopus*, and *Web of Science*.

As a first step, the search for documents containing the following main terms, in the title or abstract, was set on for each of the databases: ''Indoor Environmental Quality" (which represents the general topic of the present study), ''thermal environment", ''air quality", ''acoustics", ''lighting" (which represent the main four environmental factors, obviously related to the indoor environment). From this first step, a large number of documents was obtained for each database. The search results, with respect to the number of documents found, are summarized in Fig. 1: it is possible to point out that ''thermal environment" and ''air quality" are the terms to which a higher number of documents correspond, while ''acoustics" is the term to which the lowest number of documents corresponds for all the databases. By analysing only the results obtained from the *ScienceDirect* database, the trends over the years of the published documents, containing the searched terms, are shown in Fig. 2. In the decade 2008–2018, the trends were generally increasing (with an average annual rate of increase varying in the 15–30% range, depending on the searched term), with slight decreases in 2018. It clearly reflects the increase in journals scientific production, but it also demonstrates a growing interest in these issues, despite the fact that they have been studied for many years.

The number of the obtained results in the first step of the literature search was considered too large for a detailed analysis. So, a second step of the literature search was carried out by refining the results using some meaningful combinations of the main searched terms. These combinations have been enriched from time to time by adding keywords, synonyms or equivalent terms frequently used in the literature, such as for example (see also Table 2): ''IEQ model", ''IEQ index", ''assessment scheme", ''weighting scheme", "comfort" (with some of the most widely used adjectives such as: thermal or hygrothermal, acoustic or noise, luminous or visual, and others).

From this second step, the number of documents was reduced from about 26,000 down to about 200 documents, which were analysed in detail, with the purpose to select the significant ones for the present study. After the detailed analysis, 21 scientific documents were selected [19,21–40] among the 200 found documents. The selection was done by including the documents fitting the following criteria: publication year in the range 2002–2018, analysis carried out at least on three of the four environmental factors, and presence of numerical weighting schemes to establish their relative relevance.

2.1. Survey methods and samples of participants for subjective evaluations

For the evaluation of the combined effects of different environmental factors on the IEQ, the most widely used tool is the questionnaire. This tool allows to directly analyse the actual perception of the occupants, who are usually asked to assess the level of the perceived satisfaction.

In Table 1, the periods of administration of the questionnaires, the countries in which the questionnaire was administered, the number of respondents, the intended use of the investigated indoor environments (offices, schools or dwellings), and the questionnaire main features are summarized for each analysed document. Most of the used questionnaires were specifically designed to analyse the occupants' perception and acceptance of the indoor environment. Some questionnaires were developed in the context of wider national or international research projects and they involved a great number of respondents.

In particular, the document ID 3 (see Table 1) was developed within the European project ''Smart Controls and Thermal Comfort project" (SCATs), funded by the Community Research and Development Information Service (CORDIS) of the European Commission. In this project, between June 1998 and October 1999, 26 office buildings were investigated in five different European Counties. The document ID 8 was developed within the European project ''Health Optimisation Protocol for Energy–efficient buildings" (HOPE), sponsored by the fifth framework of the European Commission; it involved 14 organizations and nine different European countries in the period 2002–2005. A total of 69 office buildings and 95 apartment buildings were investigated in the project.

The documents ID 12, 13, and 14 were developed within the project ''Occupant Indoor Environmental Quality (IEQ) Survey and Building Benchmarking" at the Centre of the Built Environment of the University of Berkley, California. The project, whose main purpose was to provide a web–based survey tool that allows stakeholders to assess the performance of buildings, was conducted over a 10 years period, starting from 2002. The presented data involve 52,980 occupants from 351 buildings. The document ID 16 was developed within the project ''Indoor Climate and Quality of Life", organized by the Sonderborg Participatory Innovation Centre

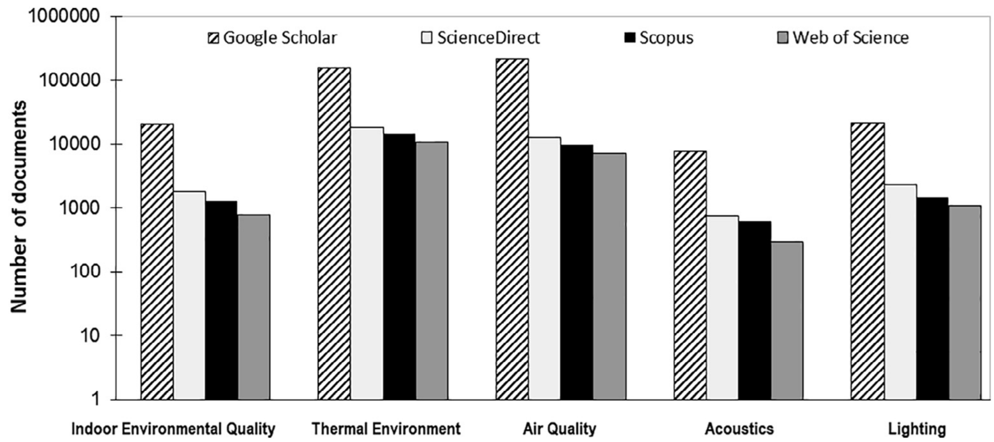


Fig. 1. Results of the literature search: numbers of found documents, in the four considered databases, grouped according to the main searched terms (the databases are not mutually exclusive, several documents can be found in more than one database).

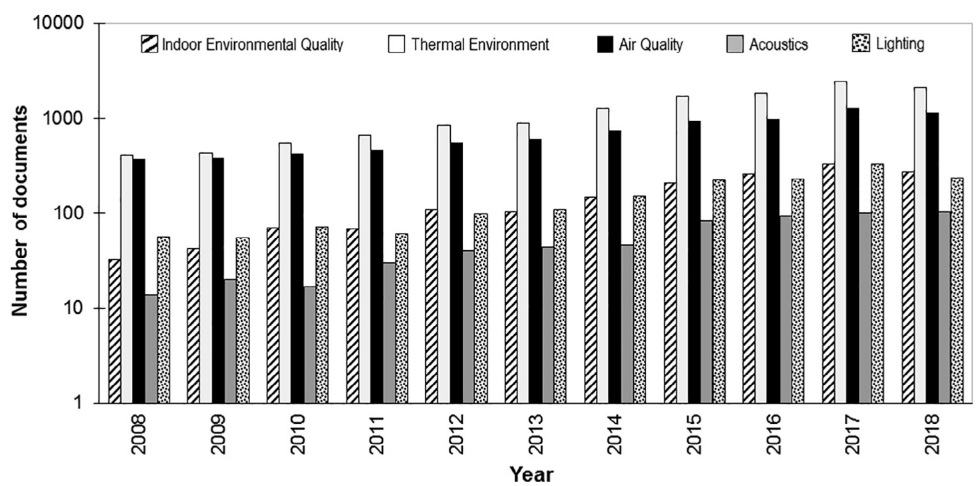


Fig. 2. Results of the literature search on ScienceDirect database: trends over the years (2008–2018) of the published documents, containing the main searched terms.

(SPIRE), funded by the Danish Enterprise Construction Authority (EBST). In this project during the period 2008–2011, five Danish companies and two university partners were involved with the idea of exploring how to engage a wider group of stakeholders in designing indoor climate products and systems.

For most of the considered documents, the surveys on the IEQ were carried out by using acceptance questionnaires. The composition and use of the questionnaires are in general briefly described, with synthetic information on the different parts that compose the questionnaires and on the type of question/answer (e.g. open–ended, dichotomous, Likert scale, etc.). As examples, for the international projects, documents ID 3,8,12,13,14, all the information on the used questionnaires are shown on the institutional websites of the projects. For the document ID 11, the text of the used questionnaire is provided as supplementary material (download available from the publisher's database). For the document ID 18, the Google drive address to download the complete questionnaire in the original language (Chinese) is included in the text. In the document ID 21, the reference to a previous paper [41], in which the used questionnaire is described and included, is provided. In the documents ID 4, 6 and 9 the related questionnaires are reported in full within the texts. Despite the large use of acceptance questionnaires, other types of questionnaire were used to evaluate the importance of each environmental factor on the IEQ. They did not always involve the building users. In some documents, the samples to which the questionnaires were administrated were small groups of experts that, on the basis of their knowledge, were asked to express a series of preferences. In these cases, the surveys were usually conducted by means of questionnaires set up with a series of pairwise comparisons. This strategy can be particularly useful when it is not possible to directly interact with the occupants. Among the considered documents, a sample of 12 experts composed of five architects, three professional engineers, and four professors was employed in the document ID 1 (see Table 1), whereas a mixed sample of 27 people composed of occupants (e.g. staff, managers, customers or clients, visitors) and experts (e.g. designers, maintenance teams) was employed in the document ID 19.

A special case is represented by the document ID 15, in which the analysed data are not obtained from the administration of questionnaires, but from a wide series of dynamic simulations of school buildings, obtained by modifying different design aspects such as shape, heated volume, glazing area, insulation level, etc. This document was also selected for the present study, because it shows an original and particularly interesting methodology for the determination of the weighting scheme.

2.2. Mathematical methods

In the considered documents, eight different mathematical methods were used by the authors to analyse the results of their subjective surveys, aiming to obtain weighting schemes. The

Table 1
Summary of the main features of the administered questionnaires described in the sample of considered documents (the list is ordered by year of publication).

ID	Authors and yearof publication	Period of administration	Countries of administration	No. of respondents	Type ofbuilding	Questionnaire main features	Ref.
1	Chiang and Lai, 2002	Not declared	TW	12	Dwellings	NO information provided.	[21]
2	Mui and Chan, 2005	1992–1995	HK	422	Offices	NO information provided.	[22]
3	Humphreys, 2005	1998–1999	FR, GR, PT,SE, UK	4655	Offices	Questionnaire composed of 7 sections, based on questions with 4–point scale answers, 5–point scale answers or 6–point scale answers, depending on the section.	[23]
4	Wong et al., 2008	Not declared	HK	293	Offices	Questionnaire based on dichotomous questions about the different analysed factors.	[24]
5	Astolfi and Pellerey, 2008	Not declared	IT	852	Schools	Questionnaire composed of 6 sections, based on 55 questions with 5–point scale answers.	[25]
6	Lai et al., 2009	Not declared	HK	125	Dwellings	Questionnaire based on dichotomous questions about the different analysed factors	[26]
7	Lai and Yik, 2009	Not declared	HK	563	Dwellings	Questionnaire composed of 2 main sections, respectively based on pairwise comparisons with 9–point scale and questions with 7–point scale.	[27]
8	Bluyssen et al., 2011	2003–2004	DE, CH, IT, FI, DK, PT, NL, UK	5732	Offices	Questionnaire based on a series of questions with 7–point scale answers.	[28]
9	Cao et al., 2012	2008–2009	CN	500	Schools, Offices	Questionnaire composed of 5 questions with 3–point scale answers.	[29]
10	Lee et al., 2012	Not declared	HK	312	Schools	Questionnaire composed of a series of questions taken from other previous studies.	[30]
11	Ncube and Riffat, 2012	2010	UK	68	Offices	Questionnaire based on a series of questions with 5–point scale answers.	[31]
12	Frontczak et al., 2012	2001–2011	USA	52,980	Offices	Questionnaire based on a series of questions with 5–point scale answers.	[32]
13	Wargocki et al., 2012	2001–2011					[33]
14	Heinzerling et al., 2013	2001–2011					[19]
15	Catalina and Iordache, 2012	–	–	–	Schools	Survey not based on questionnaires administration.	[34]
16	Frontczak et al., 2012	2011	DK	645	Dwellings	Questionnaire composed of different sections, based on close ended questions, dichotomous questions, questions with continuous scale answers, questions with variable point scale answers (from 3– to 6– point scale answers), depending on the section.	[35]
17	Ghita and Catalina, 2015	2013–2014	RO	708	Schools	NO information provided.	[36]
18	Xue et al., 2016	2013–2014	HK	482	Dwellings	Questionnaire based on a series of questions with 5–point scale answers.	[37]
19	Middelhurst et al., 2018	Not declared	UK	27	Offices	Questionnaire based on a series of pairwise comparisons with 9–point scale answer.	[38]
20	Tahsildoost and Zomorodian, 2018	2016–2017	IR	842	Schools	Questionnaire composed of different sections, based on questions with 5–point scale answers.	[39]
21	Buratti et al., 2018	2015	IT	928	Schools	Questionnaire composed of 2 sections, based on 37 questions with 11–point scale answers.	[40]

Legend: CH = Switzerland, CN = China, DE = Germany, DK = Denmark, FI = Finland, FR = France, GR = Greece, HK = Hong Kong, IR = Iran, IT = Italy, NL = the Netherlands, PT = Portugal, RO = Romania, SE = Sweden, TW = Taiwan, UK = United Kingdom, USA = United States of America.

methods are summarized in Table 2, together with the indication of the documents in which they were used and the list of the analysed environmental factors. In general, for all the considered documents the approach consists in searching for a relationship between the single environmental factor (assumed as independent variable) and the IEQ (assumed as the dependent variable).

In the documents ID 1,7,19 the Analytic Hierarchy Process (AHP) was used to obtain weighting schemes able to assess combined effects of multiple factors on the IEQ. The AHP belongs to the multi–criteria decision–making methods and it represents an accurate approach for quantifying the weights of decision criteria [42,43]. In particular in the document ID 1, a long list of factors (named by the authors *original list*) was analysed, but the AHP was applied only to a reduced list (named *adjusted list*) of environmental factors, recognized as those of significant influence on the IEQ, thermal environment, acoustics, indoor air quality, lighting, and electromagnetic fields [21].

In the documents ID 2,3,8 the Multiple Linear Regression (MLR) was used for modelling a linear relationship between each environmental factor and the IEQ. In particular, in the document ID 2, thermal comfort, aural comfort, indoor air quality, and visual comfort were considered as environmental factors, but during the regression analysis no significant correlation was found between visual comfort and IEQ [22]. In the document ID 8, the MLR was used after reducing the huge amount of data collected within the HOPE project questionnaires, by applying a Principal Component Analysis [28].

In the documents ID 9,11,14,18 the Multivariate Linear Regression (MvLR) was used, as an alternative to the MLR.

In the document ID 16 the Non–Parametric Spearman Correlation Analysis (NPSCA) was carried out, in order to investigate the relation between overall workplace satisfaction and the self–evaluated work performance.

In the document ID 15, a Multiple Non–Linear Regression (MNLR) was defined on the basis of an extensive amount of values

Table 2
Considered documents grouped by mathematical method used for the data analysis. For each document the analysed environmental factors are also indicated.

Mathematicalmethod	ID	Analysed environmental factors
AHP	1	Thermal comfort, Acoustics, Indoor air quality, Lighting, Electromagnetic fields.
	7	Thermal comfort, Noise, Air cleanliness, Odour.
	19	Thermal quality, Noise quality, Indoor air quality, Lighting quality, Ventilation quality.
MLR	2	Thermal comfort, Aural comfort, Indoor air quality, Visual comfort.
	3	Warmth, Humidity, Noise, IAQ, Lighting, Air movement.
	8	Thermal comfort, Noise, Air quality, Light.
MvLR	9	Thermal environment, Acoustic environment, Air quality, Luminous environment.
	11	Thermal comfort, Acoustics, Indoor air quality, Lighting.
	14	Thermal comfort, Acoustics, Indoor air quality, Lighting.
	18	Thermal comfort and Air quality (ensemble), Acoustics, Lighting.
NPSCA	16	Thermal environment, Sound quality, Air quality, Light quality.
MNLR	15	Thermal comfort, Acoustic comfort, Indoor air quality, Visual comfort.
MvLgR	4	Thermal environment, Equivalent noise level, Indoor air quality, Illumination level.
	6	Thermal comfort, Noise level, Indoor air quality, Illumination.
	10	Thermal environment, Aural environment, Indoor air quality, Visual environment.
PCA	5	Thermal, Acoustical, Indoor air, Visual.
	20	Thermal comfort, Acoustic comfort, Indoor air quality, Visual comfort.
POLR and MvLR	12	Amount of space, Noise level, Visual privacy,
	13	Colour and texture, Easy on interaction, Temperature, Sound privacy, Air quality, Building maintenance, Visual comfort, Building cleanliness, Workplace cleanliness.
No specific	17	Thermal comfort, Acoustics, Indoor air quality, Lighting.
	21	Hygrothermal Comfort; Acoustic comfort; Lighting comfort.

Legend: AHP = Analytic Hierarchy Process, MLR = Multiple Linear Regression, MvLR = Multivariate Linear Regression, NPSCA = Non–Parametric Spearman Correlation Analysis, MNLR = Multiple Non–Linear Regression, MvLgR = Multivariate Logistic Model, PCA = Pearson Correlation Analysis, POLR = Proportional Ordinal Logistic Regression.
Note: the analysed factors (as well as the terminology) were reported in the Table exactly as used in the original documents, although some are not properly environmental factors.

obtained from simulations. These regression models were obtained by using the black box method, in which the inputs and outputs are set from the beginning of the process, whereas the internal black box structures, which allow to find the best curve–fit function, are unknown.

In the documents ID 4,6,10 Multivariate Logistic Regression (MvLgR) models were applied respectively for the IEQ assessment in offices, schools, and dwellings.

In the documents ID 5,20 the Pearson Correlation Analysis (PCA) was performed for the relationships between the perceived satisfaction about each environmental factor and the perceived IEQ satisfaction.

The mathematical methods used in the selected documents are mutually exclusive, except for the documents ID 12 and 13, in which the Proportional Ordinal Logistic Regression (POLR) was used in combination with MvLR in order to investigate the relationship between the workplace satisfaction, the IEQ satisfaction, and the building features.

Finally, in the documents ID 17,21 no specific mathematical models were used for the creation of the weighting schemes, but they were obtained directly by the results of a restricted set of purposely created questions.

Reading Table 2, it is very interesting to note that the terms used to identify the main aspects inherent the indoor environmental quality (beyond the particular intended use of the building) can vary considerably. In general, there is a wide use of the terms "thermal comfort", "thermal environment" and "indoor air quality" to identify the thermal and indoor air aspects. On the contrary, the description of the acoustic and lighting aspects is much more complex, this is probably due to an attention to these aspects by a wide variety of specialized researchers (from biology to neuroscience, passing through medicine and engineering) and the consideration that type of the sound and visual messages sent by the surrounding environment affect its interpretation. For these reasons, the description of the acoustic and lighting aspects is made using numerous different terms, not always synonyms, for example: on one side "light", "light quality", "lighting quality", and "visual comfort", or on the other side "noise quality", "acoustic environment", "aural comfort", and "acoustic comfort".

2.3. Weighting schemes proposed for the environmental factors

The weighting schemes, proposed in the 21 considered documents for evaluating the combined effects of the four main environmental factors on the IEQ, are shown in Table 3. For a better comparison, in Table 3 the values of the weights obtained for the Thermal environment (TH), Air quality (AQ), Acoustics (AC), and Lighting (LT) are reported as extracted from the considered documents, and also normalized, so that their sum is equal to one, according to Equation (1)

$$W_{N,i} = \frac{W_i}{\sum_{i=1}^{4} W_i} \quad (1)$$

where: $W_{N,i}$ is the normalized value of the weight for the i-th environmental factor and W_i is the value of the weight for the i-th environmental factor as extracted from the considered document. The normalized values, are shown in brackets and the documents are grouped by type of buildings.

In order to correctly interpret the data reported in Table 3, some explanations are necessary. In the document ID 8, two different values of the weights (for summer and winter respectively) were proposed for each environmental factor. In the present study, being interested in the average annual conditions, the data shown in document ID 8 were managed by calculating a weighted average value on the number of respondents (for summer and winter) for each environmental factor, obtaining the weighting data of Table 3. In some of the considered documents (ID 1,3,12,19) several environmental factors were proposed in addition to the four considered in the present study (TH, AQ, AC, and LT), as shown in Table 2; for the present analysis, only the weights related to these four main environmental factors were used and normalized. Moreover, in the IEQ assessment, in the document ID 15 equal importance was attributed to each environmental factor, for this reason a weight of 0.25 was assigned to each factor in the corresponding row of Table 3.

Although reported in Table 3, the results of some studies were not used for the elaborations and comparisons described in the next sections, for different reasons. In particular, the results of document ID 2 were not used because the regression coefficient obtained by AHP for Lighting gave no significant contribution. In the document ID 7 Lighting was not considered, similarly in the document ID 21 Indoor Air Quality was not considered. In the document ID 18 Indoor Air Quality was marginally considered and included in the analysis of Thermal Comfort, so it was not possible to compare such results with those proposed in the studies where all the four main environmental factors were considered. It is also

Table 3
Summary of the weighting schemes, proposed in the literature, grouped by intended use of the building. The normalized values of the weighting schemes are shown in brackets. The normalized values are not indicated for the IDs in which one environmental factor was not considered (see the symbol "/") and for the IDs in which the weighting schemes were proposed already normalised.

Intended use	ID	TH		AQ		AC		LT	
Dwellings	1	0.16	(0.24)	0.22	(0.34)	0.15	(0.24)	0.12	(0.18)
	6	22.05	(0.38)	1.61	(0.04)	21.86	(0.38)	11.77	(0.20)
	7	0.23		0.20		0.23		/	
	16	0.48	(0.22)	0.64	(0.30)	0.52	(0.24)	0.52	(0.24)
	18	0.36		/		0.22		0.25	
Offices	2	0.42		0.09		0.28		/	
	19	0.32	(0.38)	0.12	(0.14)	0.22	(0.27)	0.17	(0.21)
	3	0.22	(0.29)	0.05	(0.47)	0.13	(0.17)	0.05	(0.07)
	4	6.09	(0.31)	4.88	(0.25)	4.74	(0.24)	3.70	(0.19)
	8	0.55	(0.28)	0.46	(0.24)	0.49	(0.25)	0.44	(0.23)
	11	0.30	(0.30)	0.36	(0.36)	0.18	(0.18)	0.16	(0.16)
	12	1.16	(0.25)	1.14	(0.24)	1.27	(0.27)	1.09	(0.24)
	13	0.12		0.20		0.39		0.29	
	14	0.34	(0.38)	0.13	(0.15)	0.15	(0.17)	0.27	(0.30)
Schools	5	0.50	(0.33)	0.32	(0.21)	0.39	(0.26)	0.29	(0.20)
	9	0.32	(0.38)	0.12	(0.14)	0.22	(0.27)	0.17	(0.21)
	10	1.16	(0.22)	0.96	(0.18)	1.99	(0.39)	1.07	(0.21)
	15	0.25		0.25		0.25		0.25	
	17	0.27		0.30		0.19		0.24	
	20	0.34		0.09		0.26		0.31	
	21	0.35		/		0.35		0.30	

important to observe that, although the documents ID 12,13, 14 were developed within the same project and used the same sample of participants, they led to different weighting schemes. This highlights the impact of the type of analysis and data selection methods (clustering) on the weighting scheme, especially when large amounts of data are available.

In Fig. 3, the box plots of the normalized weights of the four environmental factors, obtained by the considered documents, are shown. The dashed red line corresponds to the value of 0.25, which represents the case of equal importance for all the environmental factors.

It is possible to observe that TH is a very relevant aspect, with almost 75% of the normalized coefficients (data above the first quartile) higher or equal to 0.25. On the contrary, LT is frequently the factor with the normalized weight<0.25 in more than 75% of the cases. The medians for AQ and AC are instead close to 0.25. It is also possible to see a strong variability of the weights attributed to the four environmental factors; especially for thermal environment and indoor air quality it highlights a non–univocal consent of the scientific community in the acceptance of a suitable weighting scheme to assess the combined effects of multiple factors on the IEQ. As an example, it is evident as the AQ is the factor with the highest variability of the weight (interquartile of 0.14), presenting also both the minimum (0.04) and the maximum (0.47) weights among all the analysed environmental factors.

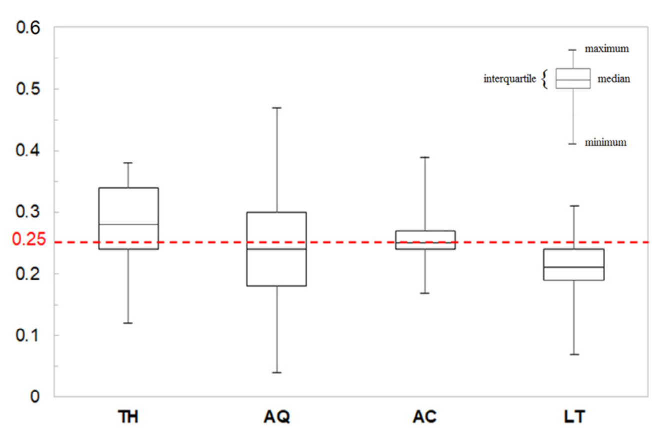


Fig. 3. Box plot of the weights obtained by the considered documents for the main environmental factors (the dashed red line corresponds to the value of 0.25, which represents the case of equal importance for all the environmental factors). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Description of the conducted surveys

Significantly different weighting schemes, as demonstrated by the review discussed in the previous Section, can be found in the scientific literature, especially since many of the studies were conducted on buildings with specific intended uses and geographical locations. Consequently, further investigations seem required to arrive at more consolidated positions. For this reason, three different surveys were conducted from May 2016 to May 2019, by using as case studies different university classrooms at the School of Engineering of the University of Pisa (Italy).

The surveys have in common the exploitation of questionnaires administered in Italian (native language of the participants) to samples of users, involving an overall number of 1468 participants, none of which participated in more than one survey. The surveys differ in the investigation methodologies. In the first survey, it was asked to the participants, via an appropriate questionnaire, to rate the acceptance of the IEQ and the acceptance of each environmental factor. In the second survey, it was asked to the participants, via an appropriate questionnaire, to create a ranking of the four analysed environmental factors (TH, AQ, AC, and LT), according to their relative relevance on the IEQ. In the third survey, the participants were asked, through a special questionnaire, to express their preferences on a series of pairwise comparisons based on the four environmental factors. The results of the first survey are obviously dependent to the specific classrooms where the questionnaire was administered, the results of the second and third surveys are instead independent from the classrooms but still referring to school buildings.

3.1. First survey: Acceptance of IEQ and of each environmental factor

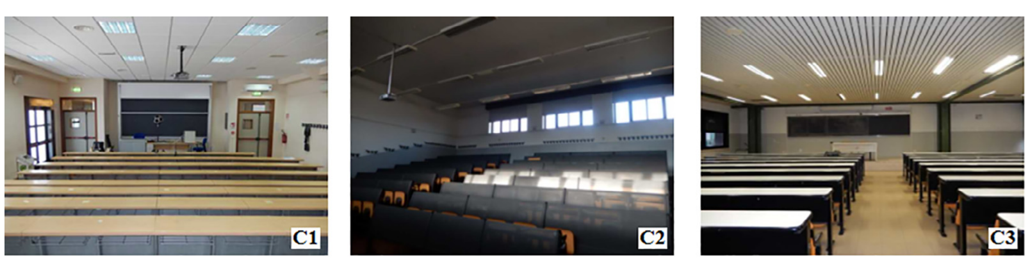
In order to assess the influence of each environmental factor on the IEQ, an acceptance questionnaire was created and administrated to a large sample of university students. The administration of the questionnaire took place in five different university classrooms (Fig. 4) and was repeated in different periods of the year, with the aim of reducing the impact of the classroom type and of the season. The classrooms involved in the survey are all intended for lessons. All the classrooms are equipped with building services solutions typically used in Italian university classrooms (e.g. air conditioning provided by air diffusers ceiling mounted, artificial lighting provided by luminaires with linear fluorescent lamps). None of the classrooms has a controlled mechanical ventilation system. The dimensional characteristics of the five classrooms used as case studies are reported in Fig. 4.

The questionnaire (*Q1*) administrated in the first survey is based on the acceptance of the IEQ and it is composed of a preliminary section and other five parts. In the preliminary section, data necessary for the characterization of the sample (age and gender) are required, whereas in the five next parts it is asked to evaluate the acceptance of the indoor environment. All the questions have a multiple choice on a 5–point Likert scale and, for an easier compilation, it was chosen a verbal scale, with the following judgments: Bad, Poor, Sufficient, Good, and Excellent. The Likert scale at odd values (5 in this case) allows the participant to choose a neutral position; for the present case, the intermediate position is the answer "Sufficient". More in detail, with the first question (Part A) it is asked to express an opinion on the overall well–being perceived in the classroom. Then the four main environmental factors are investigated, with more targeted questions regarding TC (Part B), AQ (Part C), AC (Part D), and LT (part E) factors. In creating the questionnaire, particular attention was paid to the choice of words and concepts that could were easily understood by the participants, who were university students with basic knowledge about the investigated subject. Fig. 5 shows a picture of the acceptance questionnaire administered during the research. For this survey, it was necessary that the participants were the real occupants of the university classrooms. The sample of participants was made up of 945 students, entirely from the School of Engineering of the University of Pisa. The students took part voluntarily in the research, the questionnaire was not mandatory and anonymous.

The questionnaire was administered in paper form in the biennium May 2016–May 2018. Considering that the students do not attend all the lectures in the same classroom (they may arrive in the classroom just before the start of the lecture), the questionnaire was submitted in the last minutes of each lecture (only two-hour lessons were selected for the survey). It allows the students to have a clear idea of their exposure conditions during the compilation of the questionnaire. Before the administration, the questionnaire and the purpose of the activity in progress were briefly described, but no further information was provided, in order to prevent bias. Before the analysis of the results, the transition from the verbal scale used in the questionnaire to a numerical scale, able to allow easier statistical evaluations, was applied. A numerical value from 1 to 5 was associated to the judgments expressed for each answer, according to the degree of satisfaction ("Bad"=1, "Poor"=2, "Sufficient"=3, "Good"=4, "Excellent"=5). Note that, except for the Acoustics (part C of the questionnaire *Q1*, see Fig. 5), the single environmental factors were judged using more than one question (parts B, C and E of the questionnaire *Q1*, see Fig. 5). For this reason, in each submitted questionnaire, the numerical value associated to each environmental factor was obtained as arithmetic average value of the answers to relevant questions. With these results, a multiple linear regression was applied by assuming the score of the overall comfort assessment (results of question 1) as a dependent variable and the scores of the four environmental factors (as results of the other nine appropriately aggregated questions) as independent variables. Considering that some of the environmental factors are assessed with more than one question (Fig. 5), the score assigned to each of these environmental factors was obtained averaging the scores of the related questions.

3.2. Second survey: Ranking of the four analysed environmental factors

As shown in the previous Section, the Analytic Hierarchy Process (AHP) represents a survey technique commonly used in many sectors, and it is a basic approach to decision making. In this process, the decision stems from having created a priority list of the various alternatives [42,43]. Given the adequacy of the AHP with respect to the aims of the present study, as evidenced by the interesting results obtained in previous similar investigations [1,7,19], and given the experience of the authors in using the AHP, gained in research activities carried out in the last years [18], it was decided to use the AHP to assess the relevance of each analysed environmental factor on the IEQ. This was done by exploiting the results of a specific questionnaire *Q2*, where it was asked to express a ranking of importance among the four environmental factors, according to their relevance on the IEQ in school buildings. The scale of preference varies from 1 (most important factor) to 4



	S (m²)	V (m³)	Seats
C1	156	512	139
C2	186	910	142
C3	190	550	160
C4	215	613	84
C5	216	745	216

Fig. 4. Photos and sizes of the classrooms used as case studies (S = floor area, V = net volume).

In relation to your current perception of the environment, please answer the questions using one of the following adjectives: Bad, Poor, Sufficient, Good, Excellent

Part A – Global Comfort
1- How do you rate the level of well-being perceived in the classroom during the lecture ?
Part B – Thermal Environment (TH)
2- How do you rate the temperature in the classroom ?
3- How do you rate the humidity in the classroom ?
Part C – Indoor Air Quality (AQ)
4- How do you rate the air quality in the classroom ?
Part D – Acoustics (AC)
5- How do you rate the sound insulation of the classroom from the external noise ?
6- How do you rate the sound insulation of the classroom from noise due to adjacent rooms ?
7- How do you rate the perception of the teacher voice in the classroom ?
Part E – Lighting (LT)
8- How do you rate the lighting of the classroom (artificial lighting and daylighting) ?
9- How do you rate the level of shielding of direct sunlight ?
10- During the observation of the blackboard, how do you rate the degree of shielding of lighting sources (glare effects) ?

Fig. 5. Picture of the administrated questionnaire *Q1* (first survey).

(less important factor), as shown in Fig. 6. Unlike the questionnaire *Q1*, the *Q2* is not referred to the specific classroom in which the participant is located, but intentionally referred to school buildings, so that the participants (students) can draw to their experience of classrooms and school environments overall attended.

The sample of participants in the second survey was composed of 458 students, all from the School of Engineering of the University of Pisa. Similarly to the first survey, the students took part voluntarily in the research, the questionnaire was not mandatory and anonymous. The questionnaire was administered in paper form in the period September 2017–September 2018. Immediately before the administration, the questionnaire and the purpose of the activity in progress were briefly described, and it was also specified that the answers had to be given not referring to a specific classroom, but to the general experience of having attended numerous classrooms over the years.

3.3. Third survey: Pairwise comparisons based on the analysed environmental factors

It was decided to use the AHP to assess the relevance of each analysed environmental factor on the IEQ, also exploiting the results of the third questionnaire, based on a set of pairwise comparisons of the four environmental factors. The pairwise comparison is the simplest evaluation way because comparing two elements is the most elementary method to express a preference.

The questionnaire (*Q3*), administrated in the third survey, was structured to facilitate the use of the AHP during the analysis of the results. The questionnaire consisted of a complete set of all the possible pairwise comparisons among the four analysed environmental factors (i.e. six pairwise comparisons). Fig. 7 shows a picture of the administrated questionnaire.

The evaluation scale used for the comparisons was a 9–point symmetric scale (from "Marginally strong" to "Extremely strong"), with a neutral score ("Equal"), as shown in Fig. 7. As in the questionnaire *Q2*, the *Q3* was not used to evaluate a specific classroom, but to define a ranking of importance among the four environmental factors, according to their relevance on the IEQ in school buildings. The sample of participants in the third survey was composed of 65 university students.

The reduced dimension of the used sample, especially if compared to the other surveys (see Sections 3.1 and 3.2), is in line with the methods proposed in the literature, where the pairwise comparison usually involves a small number of participants [1,19].

The questionnaire was administered in paper form in the period September 2018–May 2019. Similarly to the other two surveys, the questionnaire was not mandatory and anonymous and the students took part voluntarily in the research. The same behaviour was adopted immediately before the administration phase, with a description of the questionnaire and of the purpose of the activity, which needed to evaluate the general experience of having attended numerous classrooms over the years and not only a specific classroom.

4. Determination of weighting schemes

4.1. Weighting scheme obtained from the results of the first survey

The questionnaire *Q1* was administrated to 945 participants during the first survey, obtaining a response rate of 98.9% (10 questionnaires were not properly completed, so that they were considered invalid and neglected in the analysis). The sample was composed of 61.7% males and 38.3% females, aged in the 19–30 years range. The average age of the sample was 21.3 years (SD = 1.85) and the most part of the sample (about 70%) was aged in the 20–21 years range.

The results of the questionnaire are summarized in Fig. 8, where the average scores obtained for the IEQ and for each environmental factor are shown; they are reported for the classrooms used as case studies. The results in Fig. 8 can be discussed according to different points of view. If the classrooms are considered as a whole, it can

According to your experience about school environments and on the basis of the relative importance they have in comfort conditions, put in descending order the following four environmental factors (form 1=most important ……, to 4=less important)

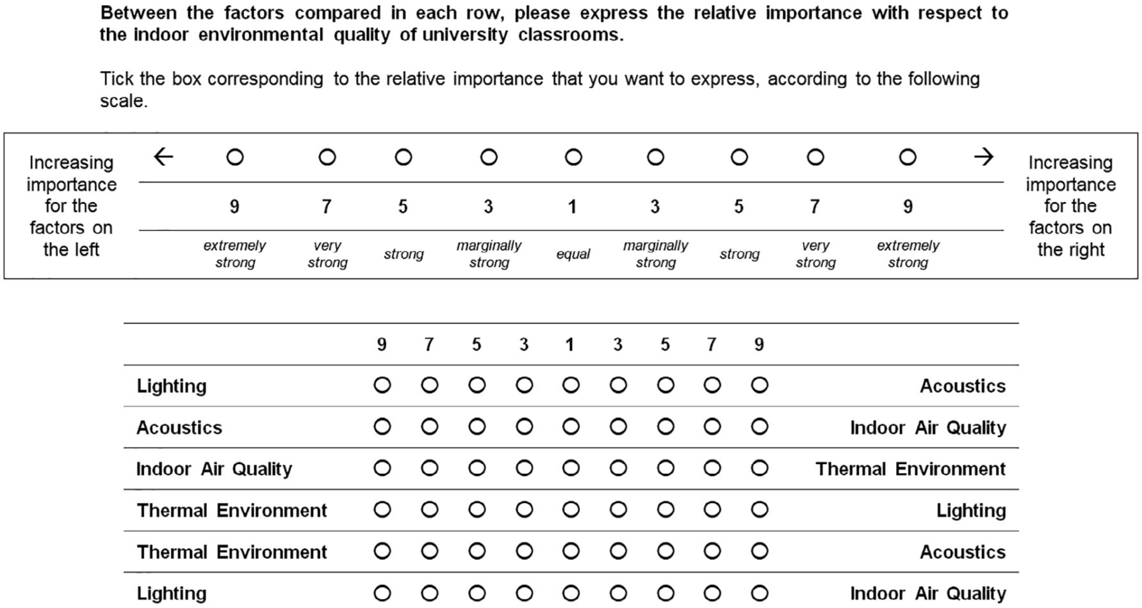
[ ] Indoor Air Quality

[ ] Lighting

[ ] Acoustics

[ ] Thermal Environment (i.e. air temperature and relative humidity)

Fig. 6. Picture of the administrated questionnaire *Q2* (second survey).


Between the factors compared in each row, please express the relative importance with respect to the indoor environmental quality of university classrooms.

Tick the box corresponding to the relative importance that you want to express, according to the following scale.

Increasing importance for the factors on the left ←	○	○	○	○	○	○	○	○	○	→ Increasing importance for the factors on the right
	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	
Lighting	○	○	○	○	○	○	○	○	○	**Acoustics**
Acoustics	○	○	○	○	○	○	○	○	○	**Indoor Air Quality**
Indoor Air Quality	○	○	○	○	○	○	○	○	○	**Thermal Environment**
Thermal Environment	○	○	○	○	○	○	○	○	○	**Lighting**
Thermal Environment	○	○	○	○	○	○	○	○	○	**Acoustics**
Lighting	○	○	○	○	○	○	○	○	○	**Indoor Air Quality**

Fig. 7. Picture of the administrated questionnaire *Q3* (third survey).

be observed that, except for C1, the other ones did not receive completely sufficient scores (greater than3), showing some gaps in achieving the comfort levels expected by the users. If the classrooms are separately considered, it can be observed that: C2 shows sufficient judgments except for AQ, for which a score of 2.40 was obtained; C3 and C4 received a sufficient judgment only for LT, for which scores of 3.12 and 3.13 were respectively obtained; C5 received the lowest scores in terms of TH (2.05), AQ (1.82), and IEQ (2.12), showing a very poor comfort level.

When considering the environmental factors, it can be observed that: AQ was the most critical one, judged not sufficient (scores from 1.82 to 2.89) in four of the five classrooms (the only exception is C1, score 3.21); IEQ and TH were judged not sufficient (scores from 2.05 to 2.98) in three (C3, C4, C5) of the five classrooms, whereas AC was judged not sufficient in C3 and C4; finally LT was evaluated sufficient in all the classrooms.

An interpretation of the results obtained from the total sample of the administrated questionnaires is shown in Fig. 9. In the bubble charts of Fig. 9, the centre of each bubble is determined by the pair of scores obtained respectively for the acceptance of a single environmental factor and for the overall acceptance (obviously the graphs are four, one for each analysed environmental factor). The size of the bubble is proportional to the number of occurrences of the pair, detected in the answers.

Since more than one question was used to estimate the perception associated with each environmental factor, the scores were calculated as the average of the values obtained from the questions related to the specific environmental factor. Observing the Fig. 9, it can be noticed that the thermal perception (Fig. 9a) seems to have the closest relation with the overall perception. In fact, the bubbles with larger diameter (greater occurrences in the answers) have the centres very close to the diagonal line of the graph (which represents all the points with thermal perception score equal to overall perception score). This aspect cannot be significantly highlighted for the other environmental factors, for which a greater dispersion of the combinations is observed. The obtained regression coefficients, together with their standard deviation (SD), t–statistics (t), and significance (p–value) are reported in Table 4. The coefficient of determination (R^2) is equal to 0.64 and, despite it is not a very high value, it is slightly higher than 0.54 obtained for the survey described in the document ID 3 [23]. It is also possible to observe that the TH represents the most important contribution

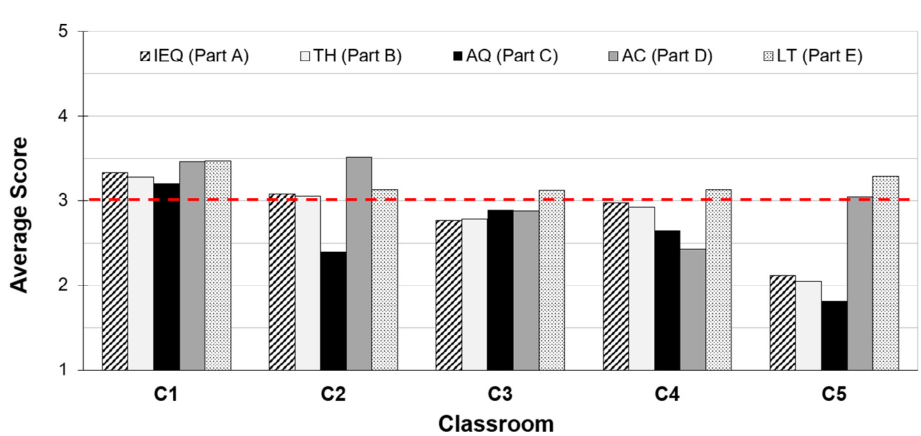


Fig. 8. Average scores obtained for the global IEQ and for each environmental factor by the questionnaire *Q1* results (the dashed line corresponds to the score of 3, i.e. "sufficient" score on the 5-point verbal scale of the questionnaire).

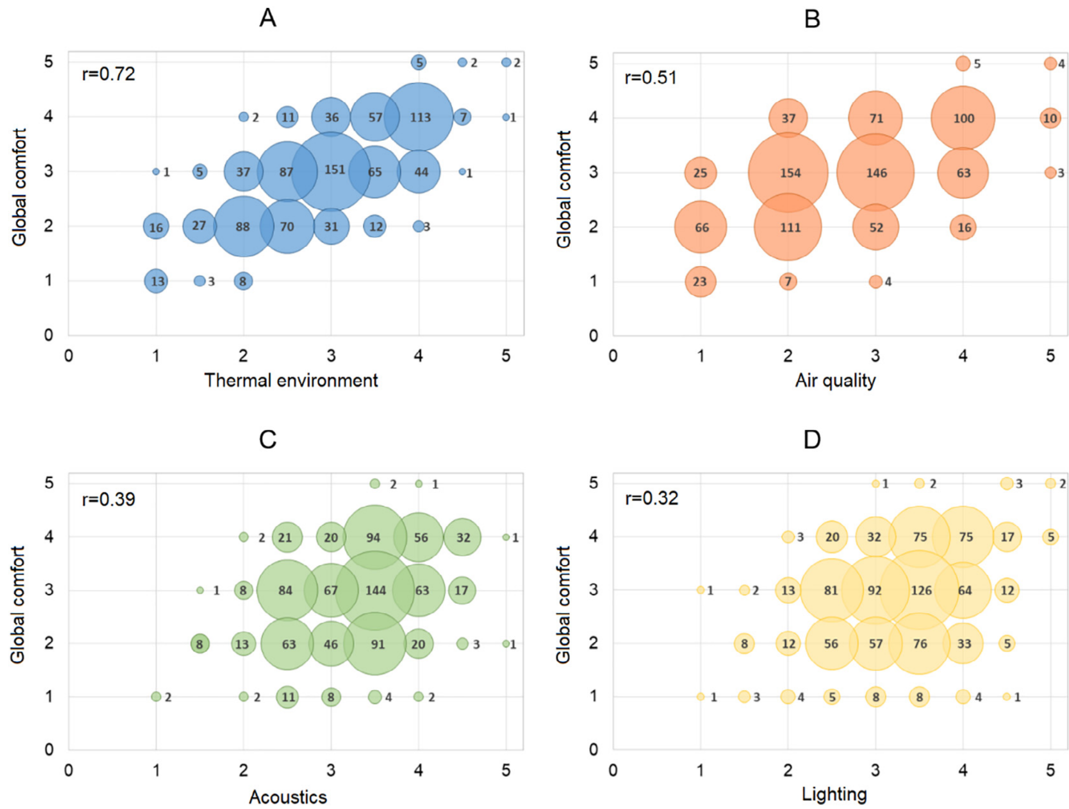


Fig. 9. Bubble charts of the answers: centre of each bubble determined by the pair of scores obtained respectively for the single environmental factor and for the global comfort; size of the bubble proportional to the number of occurrences of the pair (number indicated in the centre or near of the bubble). For each bubble chart, the obtained Pearson's coefficient of correlation (r) is indicated.

to the overall perception, followed by AC, AQ, and LT. However, AC and AQ have very close coefficients. Finally, the coefficients obtained from the multiple regression were normalized (their sum equal to 1) and the following weighting scheme was obtained: **TH = 0.41, AQ = 0.21, AC = 0.22, LT = 0.16**.

4.2. Weighting scheme obtained from the results of the second survey

The questionnaire *Q2* was administrated to 458 participants during the second survey, obtaining a response rate of 99.6% (2 of the 458 questionnaires administered were not completed). The sample was composed of 53.1% males and 46.9% females, aged in the 20–31 years range, with an average age of the sample of 25.0 years (SD = 3.8). The results of the questionnaire *Q2* were analysed calculating the sum (on the 456 filled questionnaires) of the scores obtained for each environmental factor (the lower the sum was, the more relevant the environmental factor was judged). By ordering the sums from the smallest value to the largest one, it was possible to build a ranking of relevance for the analysed environmental factors. The AHP was then applied to the ranking, obtaining the AHP comparison matrix of Table 5.

Table 4
Coefficients obtained by the application of MLR to the questionnaire *Q1* results. The overall comfort (question #1 of *Q1*) was considered as the dependent variable.

	Coefficients	SD	t	p–value
(Constant)	−0.182	0.101	−1.809	
TH	0.430	0.027	16.26	< 0.001
AQ	0.219	0.021	10.20	< 0.001
AC	0.228	0.029	7.97	< 0.001
LT	0.161	0.031	5.27	0.002

The Consistency Ratio (CR) was also calculated for the results of the survey, obtaining CR = 0.03. The calculated value of CR is lower than CR_{ref} = 0.08, which represents the reference value calculated in function of the number of the considered variables. When CR < CR_{ref} the attribution of the degrees of preference can be considered adequate and the comparison matrix consistent [42]. By applying the AHP, the following weighting scheme was obtained: **TH = 0.42, AQ = 0.12, AC = 0.19, LT = 0.27**.

4.3. Weighting scheme obtained from the results of the third survey

The questionnaires *Q3* was administrated to 65 participants during the third survey. All students correctly completed the questionnaire, so that the response rate obtained was 100%. The sample was composed of 49.2% males and 50.8% females, aged in the 20–31 years range, with an average age of the sample of 23.7 years (SD = 2.8). The results obtained from the questionnaire *Q3* were analysed calculating the answer occurrences shown in Fig. 10.

As an example, observing Fig. 10 and considering the comparison between LT and AC, LT received 3 answers with score 7, 5 answers with score 5 and 9 answers with score 3. Similarly, AC received 6 answers with score 5, 11 answers with score 3 (remember that the score equal to 1 means equal importance of the two factors). The AHP was then applied by using the answer occurrences and obtaining the AHP comparison matrix shown in Table 5. The CR was calculated for the results of the survey, obtaining CR = 0.03. For this survey too, the calculated value of CR is lower than CR_{ref} = 0.08, hence the degrees of preference can be considered adequate and the comparison matrix consistent. By applying

Table 5
Comparison matrices obtained by the application of the AHP to the results of questionnaires *Q2* and *Q3* respectively.

	Questionnaire *Q2*				Questionnaire *Q3*			
	TH	AQ	AC	LT	TH	AQ	AC	LT
TH	1	3	2	2	1	3	2	2
AQ	1/3	1	1/2	1/2	1/3	1	1	1
AC	1/2	2	1	1/2	1/2	1	1	1/2
LT	1/2	2	2	1	1/2	1	2	1

the AHP, the following weighting scheme was obtained: **TH = 0.43, AQ = 0.17, AC = 0.16, LT = 0.24**.

4.4. Comparison of the obtained weighting schemes

According to the previous sections, three different weighting schemes were obtained from the results of the three subjective surveys, carried out during the present study; they are graphically shown in Fig. 11. It is possible to observe that TH resulted the most important environmental factor in all the three surveys, with weight values in the 0.41–0.43 range. AQ, AC, and LT did not always assume the same relative importance. As found in the literature, the results for AQ were characterized by a great variability, with weight values in the 0.12–0.21 range. The results of AC showed a slightly smaller variability, with weight values in the 0.16–0.22 range. The greatest variability was observed for the results of LT, with weight values in the 0.16–0.27 range. A significant difference emerges between the weights of LT obtained from the first survey (LT = 0.16) and that of the other two surveys (LT = 0.27 and LT = 0.24 respectively). Remembering that the first survey involves the classrooms used as case study and noting that LT is the only one of the four environmental factors that was judged sufficient in all the classrooms (see Fig. 8, first survey), the satisfaction of the participants expectations about the lighting may have led the participants to give less importance to this environmental factor, especially with respect to those involved in the other two surveys.

Using all the results of the three surveys, an additional weighting scheme can be obtained, assigning to each environmental factor a weight value equal to the average value obtained in the three surveys.

An arithmetic average was used instead of the average weighted on the number of participants, as the sets of weights obtained do not depend on the number of respondents (provided they are significantly numerous), but rather on the methods of

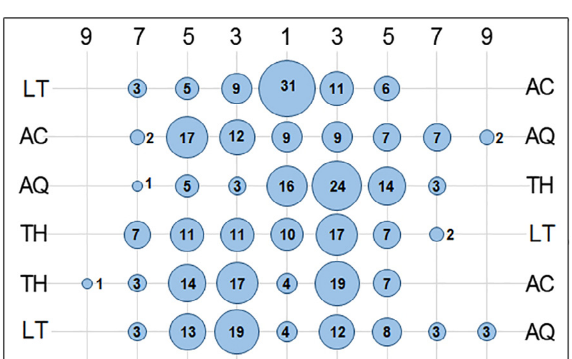


Fig. 10. Response frequencies obtained from the pairwise comparison between the four environmental factors. The size of each bubble is proportional to the number of answers, which are indicated in the centre or near of the bubble.

investigation and analysis of the collected data. This additional weighting scheme is composed as follows: **TH = 0.42, AQ = 0.17, AC = 0.19, LT = 0.22**.

5. Discussion

The importance of each environmental factor on the IEQ depends on many features, which may depend on the type of environment and on the activity carried out. For this reason, the results obtained from the literature review were further analysed and grouped in function of the building uses (offices, schools, and dwellings), as shown in Fig. 12.

The box plots of the normalized weights assigned to the environmental factors for offices (Fig. 12a) show a strong variability: TH is characterized by the highest median (about 0.30), LT by the lowest (0.22), whereas AQ and AC have similar medians (about 0.25). AQ has the maximum weight (0.47) with respect to all the collected data; TH is the factor with the smallest interquartile (data more concentrated about the median), that is completely higher than 0.25.

In the box plots of the normalized weights assigned to the environmental factors for schools (Fig. 12b), the data obtained from the three subjective surveys, carried out in the present study, were added to those obtained from the literature review. For this building use (schools) TH is characterized again by the highest median (0.30) whereas AQ by the lowest (about 0.20); LT is the factor with the smallest interquartile, that is completely lower than 0.25; AC is the unique factor that has the interquartile completely higher than 0.25. This order can be justified considering that AC is certainly very important for school buildings, being closely related to learning process. AQ can be influenced by the occupancy characteristics of the building (i.e. the university students frequently change their classroom and usually they have a different perception of the AQ with respect to those who have a continuous and stationary occupation of the rooms, as the office buildings occupants). The results obtained in the present study (see blue dots in Fig. 12b), with special reference to the weighting scheme discussed in the previous section, show that TC assumes a high normalized weight (0.42), greater than all the results presented by other researches for schools. This result was confirmed in all the three surveys carried out, in which the weight of TH is always resulted higher than 0.40 (see Fig. 11), pointing out the pronounced sensitivity that the students of the large examined sample have shown towards this environmental factor. At the same time AC assumes a normalized weight (0.19) very close to the minimum value found in literature for schools, whereas AQ and LT assume normalized weights (0.17 and 0.23 respecively) that are included in the respective interquartiles.

The box plots of the normalized weights assigned to the environmental factors for dwellings (Fig. 12c), although obtained from a restricted number of studies (ID 1,7, and 16 see Table 3), involved more than one thousand survey participants (see table 1). For dwellings, AQ and AC are characterized by the highest median (about 0.30), whereas LT by the lowest (about 0.2), TH and AC have similar medians (about 0.25). AQ is characterized by a great variability; despite the high median, it has also the minimum weight (lower than 0.05) with respect to all the collected data; LT is the factor with the smallest interquartile, that is completely lower than 0.25. Although confirmations from future studies are desirable, for this intended use AC appears as the most important factor on the IEQ.

Moreover, the average values of the normalized weights of each environmental factor were calculated considering the buildings with the same use, obtaining a single weighting scheme for each considered intended use. These values could be used to make

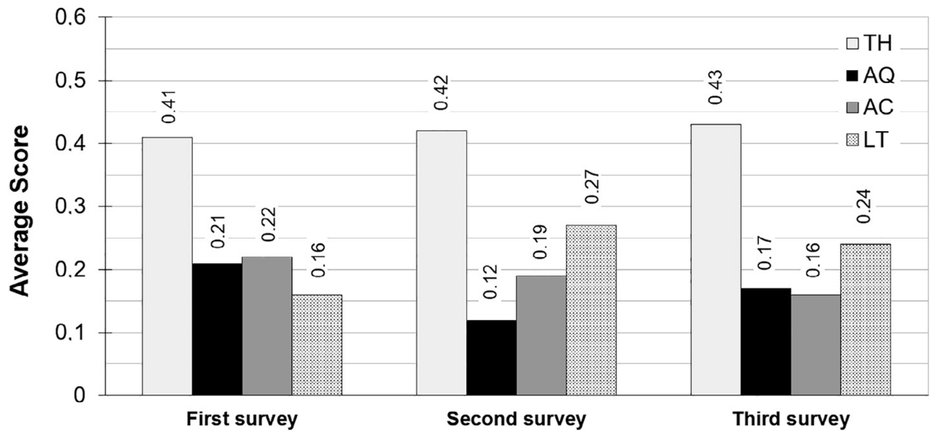


Fig. 11. Comparison of the weighting schemes obtained from the results of the different surveys.

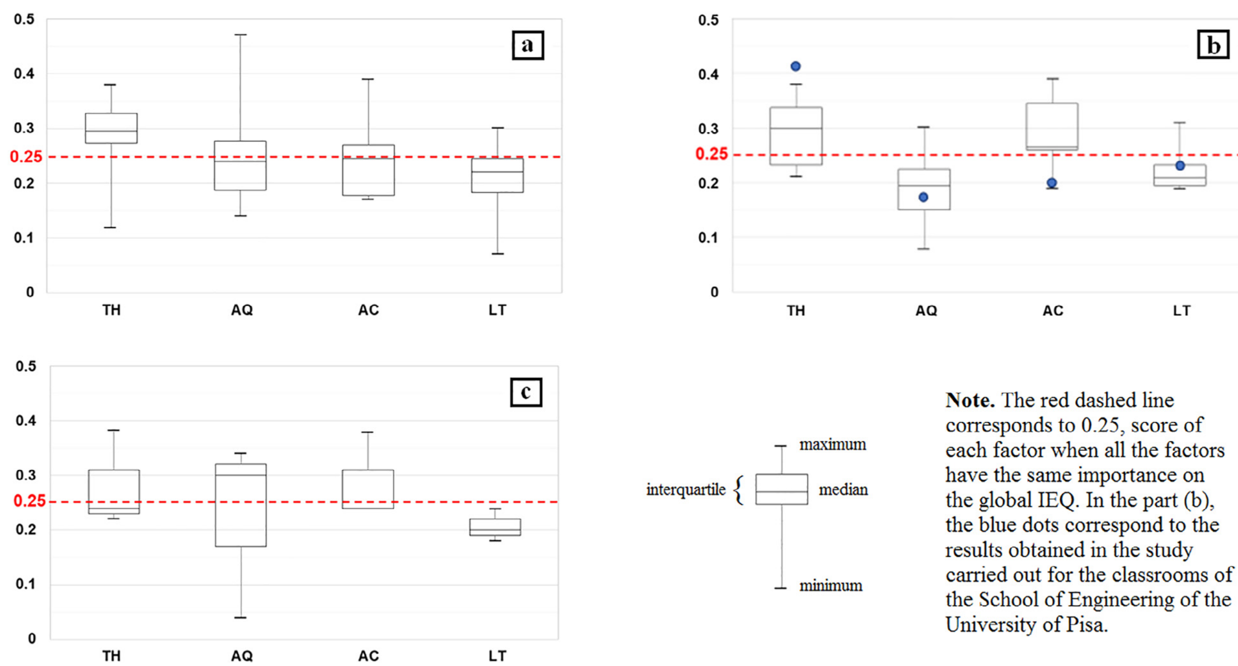


Fig. 12. Box plot of the weights assigned to each environmental factor for different intended use of the building: a) Offices, b) Schools, c) Dwellings.

assessments of the overall comfort when a subjective analysis is not possible (questionnaires administration). In detail, the average weights obtained for each bulding use are shown in the radar chart of Fig. 13. It can be observed that TH, with normalized weights in the 0.28–0.33 range is the most important factor, overcomed by AC (Fig. 13c) only for dwellings.

For offices (Fig. 13a), by ordering the environmental factors by importance, it was obtained: TH (0.29), AQ (0.26), AC (0.24), and LT (0.21); in this case AQ assumes great importance if compared to the other building uses. By operating in the same way, for schools (Fig. 13b), it was obtained: TH (0.33), AC (0.26), LT (0.22), and AQ (0.19), highlighting a smaller importance when compared to the other building uses. Similarly, for dwellings (Fig. 13c) it was obtained: AC (0.29), TH (0.28), AQ (0.22), and LT (0.21), with the great importance of AC, as observed previously.

For an easier comparison, in Fig. 13b the weighting scheme obtained from the results of the surveys carried out in the present study is reported. It is possible to observe that the normalized weights of LT and AQ obtained from the literature are very close to the normalized weights obtained by the authors. The normalized weights for TH and AC from literature are respectively lower and higher than the related normalized weights obtained by the authors. Comparing the two radars from the obtained rankings standpoint, it can be observed that on both radars the maximum importance is obtained for TH, the minimum for AQ, whereas AC and LT, which cover the intermediate positions, have reversed importance.

In the radar chart of Fig. 13d, the average values of the normalized weights obtained for all the building uses from the literature are shown. In this case, the normalized weights of the four environmental factors result ordered as follows: TH (0.30), AC (0.26), AQ (0.23), LT (0.21). Using the overall average values instead of the values determined for the specific building use, even significant errors can be made: i.e. for schools, attributing to AQ the average weight of 0.23 (instead of 0.19) leads to an overestimation of the weight of 21%. For offices, assigning to AQ the average weight of 0.23 (instead of 0.26) leads to an underestimation of the weight of about 12%; comparable underestimation (10%) is obtained for dwellings, assigning to AC the average weight of 0.26 instead of 0.29. However, currently there is no information about other uses,

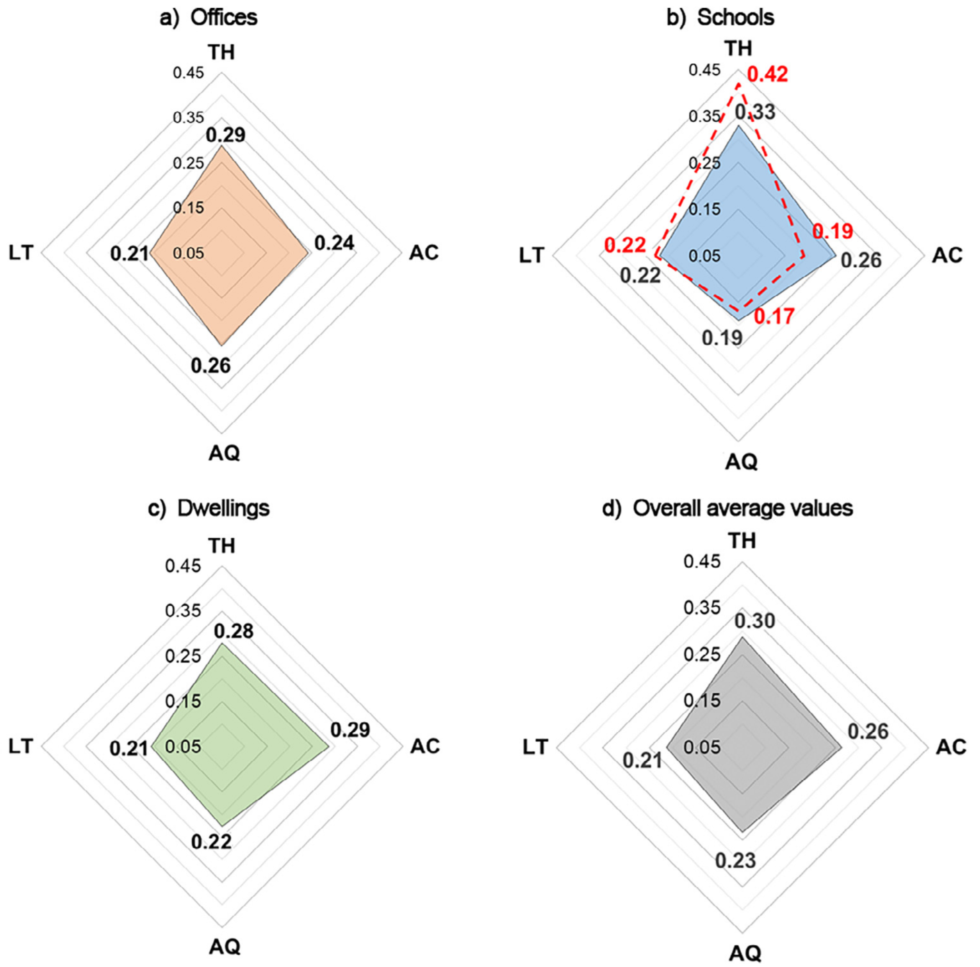


Fig. 13. Radar charts of weighting schemes obtained from the literature for different intended uses of the building: a) offices, b) schools, c) dwellings, d) overall average values. The coloured areas represent the average values found in the literature; the dashed red lines in b) represent the results obtained in the present study. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

different from those investigated in this paper (office, schools, dwellings). So that, the average normalized weights represent a possible alternative to the use of equal weights (0.25) for all environmental factors, in the case of unknown weighting scheme and no possibility to conduct subjective surveys.

6. Limitations

The present study is a contribution to the ongoing discussion in the scientific community about the holistic approaches to IEQ assessment. Due to the complexity of the topic, which involves the subjective perception of the environmental factors that characterize IEQ, the study has some limitations.

The study is based on the hypothesis that the four environmental factors are considered independent variables such as to influence the IEQ separately and with a different weight. The choice made by the authors is in line with similar studies carried out by other research groups at an international level [3,19], which allow the direct comparison of the obtained weighting schemes. However, it should be noted that there are recent studies investigating the indoor environmental quality using multi-domain approaches [44]. According to this approaches, the inter-relationships of pairs of environmental factors have been studied, in particular between thermal environment and acoustic [45–47], thermal environment and lighting [48–50], thermal environment and air quality [51], air quality and acoustics and lighting [52]. Although with not always consistent results [44], these approaches seem promising in order to evaluate any non-linearity of environmental factors towards the IEQ.

An original aspect of the study was to propose, based on the results of the literature, different weighting schemes for different intended uses of the building. In this regard, it should be noted that the schools were grouped in a single use, regardless of their levels. However, although learning activities take place, the perception and expectation of comfort may differ depending on the level (from the primary school to university). Future developments of the study could be focused on a breakdown of schools into subcategories.

In order to identify priority IEQ improvement interventions in existing buildings, it is important to note that the selection of suitable weighting schemes may depend on various aspects (in addition to the intended use investigated in this study), such as geographical area, which involves different climatic characteristics and social needs, and building construction types. In this context, the original results obtained in the present study can be considered reasonably useful for the masonry school buildings typically found in Mediterranean countries (which have climatic-social characteristics similar to those in Italy).

The limitations described, if known to the reader, are not such as to compromise the interest of the scientific community in discussing the obtained results.

7. Conclusions

Given the increasing attention posed on the indoor environmental quality (IEQ), the identification of appropriate weighting schemes to assess combined effects of multiple environmental factors on the IEQ represents an extremely relevant issue. The weighting schemes, when appropriately obtained and used, can represent a support tool in the design stage of new buildings, able to guide the choices in the direction of better users' comfort, and in the maintenance stage of existing buildings to select priority interventions for IEQ improvement.

In the present paper, the results of a literature review focused on the period 2002–2018 were analysed. On the topic of the determination and use of weighting schemes, numerous scientific studies were identified and the results of the 21 studies, deemed most interesting for the rigor and completeness of the information, were analysed in detail. Within the considered studies, more than 122,000 questionnaires were administered in 18 different countries all over the world. Various mathematical methods were used in order to define relationships between the different environmental factors and the IEQ.

From the studies found in the literature, the most relevant environmental factors are: thermal environment (TH), air quality (AQ), acoustics (AC), lighting (LT). The combined effects of these environmental factors were considered in the present study. The literature data were analysed in detail and aggregated by intended use of the building, obtaining three different weighting schemes, one for each of the following intended uses: offices, schools, dwellings. The weighting schemes can be summarized as follow: TH = 0.29, AQ = 0.26, AC = 0.24, LT = 0.21 for offices; TH = 0.33, AC = 0.26, LT = 0.22, AQ = 0.19 for schools; AC = 0.29, TH = 0.28, AQ = 0.22, LT = 0.21 for dwellings. The availability of weighting schemes dedicated to specific building uses is important for the assessments of the IEQ, as it allows to diversify the relative importance of environmental factors based on the real expectations of users' comfort, which obviously vary according to the building use. An additional weighting scheme (TH = 0.30, AC = 0.26, AQ = 0.23, LT = 0.21) was obtained considering the average values of the normalized weights for all the building uses found in the literature. The use of average values represents a possible solution for building uses for which a weighting scheme is unknown, and it is not possible to conduct subjective surveys, despite the influence of some environmental factors could be underestimated or overestimated.

Considering the great variability found in the literature data relating to weighting schemes, three different subjective surveys were carried out during the present study, involving a total of 1468 participants (students) and administrating three questionnaires (one for each survey) in university classrooms at the School of Engineering of the University of Pisa. From each survey, a weighting scheme was obtained; the schemes were similar to each other and a further weighting scheme (TH = 0.42, LT = 0.22, AC = 0.19, AQ = 0.17) was calculated considering the average values of the normalized weights of each environmental factor obtained from the three surveys. This latter weighting scheme was compared with the one obtained from the literature for school buildings, observing in particular an overestimation (of the survey data compared to that of literature) of the importance of TH and an inversion of the relative importance of LT and AQ environmental factors.

In light of what is currently available in the literature and the results obtained from this study, the most effective solution for determining adequate weighting schemes is still the development of subjective surveys for the specific case. However, this solution is not always feasible or convenient from a technical–economic point of view, in these cases, the possibility of having studies that present weighting schemes valid for the intended use and the geographical area examined becomes essential. For this reason, further studies are desirable to extend the availability of weighting schemes and to enrich the scientific debate towards widely accepted weighting schemes.

CRediT authorship contribution statement

Francesco Leccese: Conceptualization, Formal analysis, Methodology, Investigation, Data analysis, Writing original draft Writing review & editing, Funding acquisition. **Michele Rocca:** Conceptualization, Formal analysis, Methodology, Investigation, Data analysis, Writing original draft Writing review & editing. **Giacomo Salvadori:** Conceptualization, Formal analysis, Methodology, Investigation, Data analysis, Writing original draft Writing review & editing, Funding acquisition. **Elisa Belloni:** Conceptualization, Formal analysis, Methodology, Investigation, Data analysis, Writing original draft Writing review & editing. **Cinzia Buratti:** Conceptualization, Formal analysis, Methodology, Investigation, Data analysis, Writing original draft Writing review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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