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Indoor air quality audit implementation in a hotel building in Portugal

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ABSTRACT

Hotels are designed to provide high levels of comfort for guests; however, frequent complaints related to uncomfortable thermal environment and inadequate indoor air quality (IAQ) appear. On the other hand, there is little research concerning IAQ audits of hotels up to now.

This study is aimed to establish and demonstrate the comprehensive IAQ audit approach for hotel buildings, based on Portugal national laws. A 4-star hotel building in Portugal is used as a case study to demonstrate the IAQ audit application and evaluate its comprehensiveness and usefulness to the hotel or facility managers. The systematic approach involves the measurement of physical parameters – temperature (dry bulb), relative humidity and the concentration of the suspended particulate matter (PM10) – the monitoring of the concentrations of selected chemical indicators – carbon dioxide (CO2), carbon monoxide (CO), formaldehyde (HCHO) and total volatile organic compounds (TVOCs) – and the measurements of biological indicators (bacteria, fungi, Legionella). In the present case, air exchange rates are measured by the concentration-decay method using metabolic CO2 as the tracer gas.

The comprehensive IAQ audit revealed four main problems in the hotel building: (1) insufficient ventilation rate; (2) too high particle concentration in some rooms; (3) contamination by Legionella of the sanitary hot-water circuit; (4) poor filtration effectiveness in all air handling units (AHUs).

1. Introduction

Hotels are designed to provide high overall comfort and multi-faceted services to guests frequently accustomed to, and willing to pay for exclusive amenities, treatment, and entertainment. Comfortable indoor environment, safety, and reliability are some of the amenities valued by guests. However, little research has been published about the indoor air quality (IAQ) of hotel buildings up to now and most hotel managers often ignore these important issues [1,2]. On the other hand, state-of-the-art technical infrastructure is typically utilized in hotels to provide high levels of comfort, especially thermal comfort. Nevertheless, using energy-intensive space-conditioning systems does not warrant absolute guest’s satisfaction [1,3]. Guests frequently complain about thermal discomfort, even where expensive and sophisticated systems are operated. Complaints in hotels are most commonly related to uncomfortable air temperatures (too high or too low), and to the difficulty or impossibility of individual adjustment [3]. Moreover, space conditioning (heating, cooling, and ventilation for the purpose of maintaining high standards of air quality and thermal comfort) typically accounts for about half the total energy consumed in hotels [4,5]. Hence, most hotel designers and managers always pay attention only to the energy consumption of hotels operation. Managers take the management of resources as a major role that inevitably leads to housekeeping’s greater emphasis on those tasks with visual satisfaction. Nevertheless, hotels are public places accommodating a vast variety of international travellers; therefore the demand for good IAQ may be higher than for other types of buildings [6].

Teeters et al. [6] claimed that facility managers in the hospitality sector have only reacted to those IAQ problems that have caused immediate irritation to guests or employees. However, inadequate air quality as well as the lack of air circulation is another frequent complaint. In addition, the IAQ of hotel buildings affects the health of guests especially in terms of bacterial contamination. For example, Legionnaire’s disease broke out in one USA hotel (182 people ill and 29 deaths in 1976) and more than 60 outbreaks worldwide in hotels, hospitals and ofﬁces were reported [7–9]. Furthermore, the severe acute respiratory syndrome (SARS) broke out in “M” hotel in Hong Kong has increased the public awareness to indoor air quality of hotels [8].

On the other hand, the European Parliament and Council approved in December 2002 a directive on the energy performance of buildings 2002/91/EC (EPBD) [10], which introduced the obligation of energy certiﬁcation of buildings. European Standardization Organization (CEN) has drafted several standards to help the member countries implementing the directive. One of these is the “Indoor environmental input parameters for design and assessment
of energy performance of buildings”, addressing IAQ, thermal environment, lighting and acoustics [11]. The standard specifies design values for indoor environment, values to be used in energy calculations, and methods to verify the specified indoor environment in the buildings [12]. However it does not establish a methodology for IAQ audits of buildings. Portugal, as one of the European Union member states, approved a series of national laws to implement the EPBD [13–15], stating simultaneously that IAQ monitoring of the existing non residential buildings is mandatory, under the rules of RSECE [14]. However, it is not the case for most of the member countries.

In this scope, a comprehensive IAQ audit methodology along with energy audit of buildings should be established in order to identify the indoor air problems. Although, some IAQ monitoring methods have been developed in different countries, most of them are applied to office and hospital buildings [e.g. Ref. [16]]. However, the IAQ monitoring approach that is suitable for the hotel building has not yet been developed [1].

Hence, the purpose of this study is to develop and demonstrate a comprehensive IAQ audit methodology for hotel buildings. The data collected from this approach can be used to assess the air quality in hotel buildings and to identify the indoor air problems. Consequently, the IAQ audit approach proposed here may be helpful for the hotel managers to reduce the health risk from hotel buildings and increase the comfort for guests. Furthermore, the result from IAQ audit shows the necessity of having IAQ audit along with energy audit of buildings. In fact, if just energy parameters are considered, as in the last decades, people’s comfort and health can be significantly sacrificed.

2. Indoor air quality audit

2.1. IAQ audit methodology

The proposed IAQ audit follows a systematic approach with portable equipment, involving the measurement of physical parameters (temperature (dry bulb), relative humidity and the concentration of the suspended particulate matter (PM_{10})), the monitoring of the concentrations of selected chemical indicators (carbon dioxide (CO₂), carbon monoxide (CO), formaldehyde (HCHO), and total volatile organic compounds (TVOCs)), and the measurements of biological indicators (bacteria, fungi, Legionella). In the reported case, air exchange rates (AERs) were measured by the concentration-decay method using metabolic CO₂ as the tracer gas. The IAQ audit commences with the collection and analysis of the available architectural, mechanical and electrical drawings follows by the walkthrough inspection in order to verify and update the information provided by the building owner or responsible agent, as well as observation for any apparent or potential pollutant sources, occupant’s activities and complaints, swift verification of CO₂ levels in the building, pre-evaluation of the hygienic and maintenance conditions of the HVAC systems, and collection of additional information which is deemed necessary for an adequate audit planning.

All collected information on the building and its HVAC systems, including during the walkthrough inspection, is considered to determine the quantity and locations of the required sampling points, a crucial task for the suitable planning of the measuring campaign. The next stage of the audit involves the measurement of the specified indicators, followed by the evaluation phase. In this phase, the measured data will be analyzed and compared with standards/regulations specified limits and the sources of IAQ problems will be identified, with the help of an integral correlation between all indicators measured and information acquired. Finally a set of corrective actions will be recommended to the building owner/manager.

Table 1

| Level | Zone Location description | Area (m²) | Max. occupancy | HVAC system | No. of measuring points |
|-------|---------------------------|-----------|----------------|-------------|-------------------------|
| 1     | A Restaurant              | 147       | 100            | AHU3        | 2                       |
|       | B Conference room 1       | 120       | 110            | AHU2 and MEF4 | 2                      |
|       | C Conference room 2       | 99        | 60             | AHU4 and MEF4 | 2                      |
| Ground | D Reception and lobby     | 541       | 65             | AHU1        | 4                       |
|       | E Business centre         | 31        | 4              | AHU1 and split | 1                      |
| 1–7   | F Rooms and suites        | 3332      | 2 per room     | MEFs        | 15                      |
| Roof  | G Exterior                | –         | –              | –           | –                      |

AHU: air handling unit. MEF: mechanical exhaust fan.

2.2. Building characteristics

To better illustrate the proposed IAQ audit methodology of hotel buildings, a 4-star hotel building in a city at the central region of Portugal was selected as a case study. This international hotel was built in 1990 and its interior space has been decorated in 1992. It is a twelve-storey building, including four underground levels. The underground levels are mainly the car parking areas, with the exception of –1 level, in which a restaurant, kitchen and 2 conference rooms are situated. Lobby, reception desk and business centre are situated in ground level. The hotel has 120 rooms and 13 suites distributed by 7 floors with a similar architecture, from 1st level to 7th level.

The HVAC system for the whole building is based in a centralized hot/chilled water production system, with a two-pipe distribution and a fan coil unit (FCU) in each guest room. The guest rooms are naturally ventilated: the sole mechanical ventilation element in each one is the exhaust fan at the respective adjacent bathroom. By this way, the fresh air supplied to the rooms and suites comes in by infiltration through the window frames and from the corridor through the door slits, strongly promoted by the bathroom mechanical exhaust fan. The ground level (lobby, reception, etc.) is served by a specific air handling unit (AHU) with a fraction of air recirculation. The air renewal and thermal conditioning for conference and meeting rooms, as well as for the restaurant is provided by all-fresh AHUs.

2.3. Preliminary visit and measurements

2.3.1. Preliminary visit

A walkthrough inspection and checklist was completed for the hotel to document HVAC system operation and hygiene, air intake location, sources of contaminants, building drainage, roof and interior inspection, maintenance, combustion appliances, room area and volume, carpets, special facilities, space usage and other factors. Photos of each visited points were taken. Floor plans and other information regarding the hotel were obtained.

2.3.2. Number and location of sampling points

After the collection of all the mentioned data, an integrated analysis of the hotel building was done to determine the quantity and locations of the sampling points. All spaces of the building with human occupancy were grouped by zones. Accordingly, the hotel building was divided into 7 different zones based on the ventilation system supplying each zone, the type of activity in the zone, thermal loads, and source of emissions.

Brief overview of the zones and number of measuring points, as well as their corresponding HVAC system are presented in Table 1.
The minimum number of sampling points to be considered in each zone was estimated as suggested in the national IAQ guideline (technical note NT-SCE-02, 2009 [17]):

\[ N_i = 0.15 \times \sqrt{A_i}, \]  

where \( N_i \) is the minimum number of sampling points in zone \( i \) \((N_i \geq 1)\), and \( A_i \) is the area of zone \( i \) in \( m^2 \).

Therefore, for this project the mentioned indicators were measured in 7 zones which encompass 27 points in total. Nevertheless the main area of concern for this IAQ audit is the set of guest rooms, as they are naturally ventilated and lack of good IAQ was much probable. Moreover one of the most important areas of hotels is the guest room where maximum comfort is critical to the success of the hotel [18]. Therefore, we will just provide the result from zone (F) which is the specified zone for guest rooms including suites. Fig. 1 shows the locations of the sampling points for sixth level. Spatial position of sampling points are specified in accordance to the international guideline EN ISO 16000-1 [19]: at least 1 m away from walls in the room, and about 1 m above the floor, since this is the approximate height of the average breathing zone.

2.3.3. Physical indicators

The thermal comfort level of the indoor environment is measured using an indoor climate analyzer DirectSense IAQ (Model IQ610, Graywolf), which allowed measuring the room ambient temperature (dry bulb) and relative humidity, besides the concentration of several chemical pollutants referred in the next section. The concentration of airborne particulate matter (PM\(_{10}\); for particles of size \( \leq 10 \) \( \mu m \)) was measured using an airborne particle counter (Model Handheld 3016 IAQ, LIGHTHOUSE).

Since it was found very probable during preliminary visit that the ventilation rate in the guest rooms was insufficient, AER measurement became inevitable. The AER in the room was measured using the concentration-decay method, in which metabolic CO\(_2\) was selected as the tracer gas [20–24]. The IAQ monitor (Model PS32, SENSTRON) was used for three days CO\(_2\) measurements.

2.3.4. Chemical indicators

Continuous real-time chemical monitoring of carbon dioxide (CO\(_2\)), carbon monoxide (CO), formaldehyde (HCHO), and total volatile organic compounds (TVOCs) was carried out at the predetermined indoor sampling points of each specified zone or group of spaces, at about 1 m above floor level and an outdoor point in close proximity to the fresh air intake point of the AHU, for a period of 15 min at each point. All the above chemical indicators were measured with DirectSense IAQ (Model IQ610, Graywolf), with the exception of formaldehyde (HCHO) which was measured with Formaldehyde Gas Detector (Model FP-30, RIKEN KEIKI Co., Ltd.).

2.3.5. Biological indicators

A portable air sampler (SAS Super IAQ, pb international CO.) for semi-solid medium (Agar plates) with a constant air flow rate of 100 L/min was used to carry out the biological sampling for

![Fig. 1. Typical room level plan (6th level).](image-url)
determining the concentration of bacteria and fungi in the air. The medium used for the collection and further laboratorial culture of bacteria was tryptic soy agar (TSA), while the collection of fungi was made on malt extract agar (MEA). Each of these measurements was taken over a period of 2.5 min to get an air sample of 250 L. After incubation in laboratory under specific temperature conditions, each plate is analyzed and the results of counting are expressed in colony-forming units per cubic meter of air (CFU/m³). Legionella is another biological indicator which should be monitored. An effective sampling of Legionella depends upon a correct water sampling, considering relevant factors such as the choice of sampling location, presence of water treatment products or the need to disinfect the sampling point. The sampling criteria are defined in the national IAQ guideline (technical note NT-SCE-02 [17]), regarding this study are summarized in Table 2.

In order to ensure the suitability of the measuring equipment, the ranges and accuracy of the measurement instruments used in this study are summarized in Table 2.

3. Results and discussion

3.1. Physical indicators

3.1.1. Assessment of the air exchange rate

Since the rooms have no dedicated supply of outdoor air, it was decided to perform a monitoring campaign of CO₂ measurements to assess the adequacy of the AER by infiltration and, if it is the case, find an appropriate remediation action. The IAQ monitor PS32, configured to a sampling interval of 1 min, was left during three days in suite #620.

The fresh air flow rate through a room is usually evaluated using one of the three tracer-gas methods: concentration decay, constant emission or constant concentration method [23]. In this project, the tracer gas concentration-decay method was selected. This is the most basic method for measuring AER and it is used to obtain discrete AER over short periods of time. In this method a certain amount of tracer gas is introduced to the room and then it is mixed with the indoor air to get its uniform concentration in the whole room. Then the gradually decreasing concentration of tracer gas in the air is recorded. In the simplest case the tracer gas may be carbon dioxide introduced in the room in a natural way, through the air exhaled by people staying in that room.

The AER (h⁻¹) in this method is determined through the analysis of the decay of CO₂ concentration in the room, after the source of such gas has been stopped, i.e., after the occupants have left the room. So, for a decay period (t – t₀) starting from an assumed uniform CO₂ concentration C₀ in the room, the integration of an overall mass balance leads to

\[ C(t) - C_{ext} = (C_0 - C_{ext}) \cdot \exp[-AER(t - t_0)] \]  \hspace{1cm} (2)

where C(t) is the observed CO₂ concentration at time t, and C_{ext} is the CO₂ concentration in the outdoor air. All the CO₂ concentrations are expressed in ppm.

Equation (2) can be made explicit for AER (h⁻¹):

\[ AER = \frac{-1}{t - t_0} \ln \left( \frac{C(t) - C_{ext}}{C_0 - C_{ext}} \right) \]  \hspace{1cm} (3)

The direct estimation of the AER through equation (3) is easy when conditions are stable regarding the fresh air flow rate, the CO₂ concentration in outdoor air and the flow pattern inside the room. However equations (2) and (3) apply to the case of a uni-zone room having air exchanges only with outdoor environment. In the present case, as the room door is very tight and the corridor is most of the time unoccupied, it was concluded that the studied room could be considered a uni-zone compartment. Regarding the uniformity of the distribution of the CO₂ concentration inside the room, it was not possible to put in practice, previous to the decay phase, the recommended procedure of using a fan during a short period to promote a good dilution, on account of the hotel guests privacy issues. Nevertheless, it was latter checked that in a similar room where an equilibrium concentration of 1100 ppm had been achieved after the sleeping period, the spatial variability of CO₂ concentration was in the order of ± 15 ppm. In rooms where there is not a strong ventilation flow, spatial non-uniformities of CO₂ concentrations tend to be lower.

A previous smoothing procedure may be recommended to minimize the disturbing influence of imprecision due to the fluctuating feature of the recorded C(t) data, as it is the case of gas analyzers with imprecision higher than ±30 ppm. Parameters were estimated by fitting the logarithm of the concentrations against time. Fig. 2 shows the first day evolution of CO₂ concentration in suite #620, before any remediation action. A curve fitting, with a linear law for a chosen concentration-decay period is shown in Fig. 3, indicating an AER of 0.429 h⁻¹. The value of AER estimated by this method was robust, i.e., regression achieved a correlation coefficient R = 0.9978, which means that conditions were quite stable. The represented decay period corresponds to a calm day

![Fig. 2. One-day CO₂ concentration measurement in the selected hotel suite (suite #620).](image-url)

![Fig. 3. Linear regression for a chosen concentration-decay period, i.e. when the occupants left the room.](image-url)
with low wind velocity ($v < 2 \text{ m/s}$), thus it represents the worst case regarding AER conditions in the studied room.

It is seen from Table 3 that by the 0.429 h$^{-1}$ AER, the amount of fresh air (coming into the room by infiltration) provided to suite #620 in the considered decay period was 20 m$^3$/h/person, which is lower than the minimum requirement stated by national IAQ regulation (RSECE [14]) for design project of hotel rooms in new buildings which is 30 m$^3$/h/occupant.

Consequently, it was suggested to the hotel technical management to keep the bathroom mechanical exhaust fan working during the night period. In Fig. 4 the time evolution of CO$_2$ concentration during a day after prescribing the new control policy for bathroom mechanical exhaust fan is presented. Accordingly, the fresh air flow rate raised enough to keep the CO$_2$ concentration within an acceptable level during the whole period with the total occupancy of the room, regarding the second compliance criterion for CO$_2$ in existing building, based on national IAQ guideline [17], which indicates an average CO$_2$ value lower than 1500 ppm, during the whole occupancy period (see Section 3.2.1 for further details).

### 3.1.2. Evaluation of thermal comfort

The measured thermal comfort parameters during 2 days measurement campaign (28–29 March 2009) are listed in Table 4. The average air temperature recorded in each guest room ranged from 23 to 24.0$^{\circ}$C. This is within the recommended range according to ASHRAE design criteria [18]. The temperature in the cold season (winter) should vary between 23 $^{\circ}$C and 24 $^{\circ}$C, in the hot season (summer) between 23 $^{\circ}$C and 26 $^{\circ}$C, relative humidity should be between 30% and 35% in winter, 50% and 60% during summer and air velocity should not exceed 0.2 m/s in the guest room. Too cold temperature will not only make guests uncomfortable, it will also result in more energy consumption in air-conditioning. The average relative humidity of each room ranged from 31.5% to 35%, which is within the recommended range (30–35%). The mean air velocity in the rooms was not measured because it was clearly found unnecessary.

### 3.1.3. Evaluation of particulate pollution

The recommended threshold level for the concentration of suspended particulate matter (PM$_{10}$) in indoor air is 150 $\mu$g/m$^3$ in Portugal [14]. Table 5 shows the measured values of indoor concentration of PM$_{10}$, which overcome the threshold level in two of the monitored rooms of the 6th floor. It should be mentioned that these measurements were conducted shortly after the cleaning operation of the rooms. Further tests proved an increase of the PM$_{10}$ concentration after vigorous walking in the rooms, which suggested that the detected suspended particulate matter originated from the floor carpet, where it was somehow deposited. A recommendation for implementing an improved technique and more frequent cleaning was given to the hotel management.

### 3.2. Chemical indicators

#### 3.2.1. Carbon dioxide (CO$_2$)

The concentration of carbon dioxide in the specified sample points varied between locations, and reached values as high as 1710 ppm. During night hours, the concentration level of CO$_2$ increased due to the constant metabolic emission by the guests in the rooms and the AER revealed to be insufficient. Regarding the CO$_2$ concentration, the verification of compliance with the national regulation limit value (1000 ppm) must take into account the actual occupancy of the room. For this purpose, the technical note NT-SCE-02, 2009 [17] suggests the following criterion:

$$\left(\frac{[\text{CO}_2]_{\text{MedT}}-[\text{CO}_2]_{\text{Ext}}}{N_{\text{ocup}}\text{max}}\right) \times \frac{N_{\text{ocup}}\text{max}}{N_{\text{ocup}}} + [\text{CO}_2]_{\text{Ext}} \leq [\text{CO}_2]_{\text{MR}} \quad (4)$$

where $[\text{CO}_2]_{\text{MR}}$ is reference limit value of CO$_2$ concentration, 1800 mg/m$^3$ (corresponding to 1000 ppm at standard pressure and 25 $^{\circ}$C [10]), $[\text{CO}_2]_{\text{Ext}}$ is the CO$_2$ concentration in the outdoor air (400 ppm for this case), $[\text{CO}_2]_{\text{MedT}}$ is time-averaged concentration of CO$_2$ in each sampling point in ppm, $N_{\text{ocup,max}}$ is maximum allowed number of occupants in the room or space, $N_{\text{ocup}}$ is the actual number of occupants during the measurements.

For the case of existing buildings, if this first criterion is not fulfilled, a second one is recommended that allows an increase of 50% of the threshold level, but implies measuring and averaging the
CO₂ over the full period of occupancy. This second criterion may be expressed as:

\[
\frac{\left(\text{CO}_2\right)_{\text{MedT}} - \left(\text{CO}_2\right)_{\text{Ext}}} {\left(\text{CO}_2\right)_{\text{Ext}}} \leq \frac{\left(\text{CO}_2\right)_{\text{MR}} \times 1.5} {\left(\text{CO}_2\right)_{\text{Ext}}}
\]

(5)

where \(\left(\text{CO}_2\right)_{\text{MedT}}\) is now the time-averaged \(\text{CO}_2\) concentration for the extended period.

The time-averaged concentration of \(\text{CO}_2\) is calculated by the following expression:

\[
\left(\text{CO}_2\right)_{\text{MedT}} = C_T = \frac{\sum \Delta t_i \times C_i} {T}
\]

(6)

where \(C_i\) in ppm is the pollutant concentration at time \(t_i\), \(\Delta t_i\) is the sampling measurement period, and \(T\) is the total measurement period.

Fig. 2 shows the time evolution of the measured \(\text{CO}_2\) concentration in suite #620 occupied by only one guest. It may be concluded that the guest entered the suite at 22:15 and left at about 07:10. Thus, taking \(\Delta t_i = 1\) min and applying expression (6) in this occupancy period, we obtain \(\left(\text{CO}_2\right)_{\text{MedT}} = 1128\) ppm. Considering \(N_{\text{ocup,max}} = 2\) for suites, the left hand side of expressions (4) and (5) will become:

\[
\frac{\left(\text{CO}_2\right)_{\text{MedT}} - \left(\text{CO}_2\right)_{\text{Ext}}} {\left(\text{CO}_2\right)_{\text{Ext}}} \leq \frac{\left(\text{CO}_2\right)_{\text{MR}} \times 1.5} {\left(\text{CO}_2\right)_{\text{Ext}}}
\]

which exceeds by 86% and 24% the limits for the first and the second compliance criteria, respectively (i.e., 1000 ppm and 1500 ppm).

After implementing the prescribed control policy for bathroom mechanical exhaust fan, as shown in Fig. 4, the average concentration is \(\left(\text{CO}_2\right)_{\text{MedT}} = 927\) ppm during the occupancy period from 21:30 to 7:30. Thus the left hand side of expression (5) will become:

\[
\frac{\left(\text{CO}_2\right)_{\text{MedT}} - \left(\text{CO}_2\right)_{\text{Ext}}} {\left(\text{CO}_2\right)_{\text{Ext}}} \leq \frac{\left(\text{CO}_2\right)_{\text{MR}} \times 1.5} {\left(\text{CO}_2\right)_{\text{Ext}}}
\]

Therefore the corrective action led to compliance of the \(\text{CO}_2\) concentration with the second criterion.

3.2.2. Carbon monoxide (CO)

The maximum reference value for CO concentration is 12.5 mg/m³, corresponding to 10 ppm according to national IAQ regulation [14]. In this study (guest rooms with no smoking activity) the measured CO concentration ranged from 0.0 to 0.6 ppm, values that are well below the recommended thresholds.

3.2.3. Formaldehyde (HCHO)

The concentrations of formaldehyde measured in this study were below 0.01 ppm, therefore in compliance with the national regulation (threshold level of 0.08 ppm). Generally, the high concentrations of formaldehyde are attributed to the materials used for interior decoration, as well as the emission from the detergents and cleaning agents.

3.2.4. Total volatile organic compounds (TVOCs)

The threshold value for total volatile organic compounds in the indoor environment in Portugal is 0.6 mg/m³ corresponding to 0.26 ppm (referred to isobutylene) or 0.16 ppm (referred to toluene) [14]. It is observed that the maximum concentrations of TVOCs in the selected rooms are 0.2, 0.17 and 0.18 mg/m³, and these are below the threshold value. Generally, the high concentrations of TVOCs in the hotel rooms are attributed to the emission from the detergents and cleaning agents used by the housekeepers when cleaning the room.

| Location          | CO₂ (ppm) | CO (ppm) | Formaldehyde (HCHO) (ppm) | TVOCs (mg/m³) |
|-------------------|-----------|----------|--------------------------|--------------|
| Suite #620        | 469       | 0        | <0.01                   | 0.2          |
| Room #613         | 426       | 0        | <0.01                   | 0.17         |
| Room #603         | 488       | 0.6      | <0.01                   | 0.18         |
| Outside air       | 396       | 0        | <0.01                   | 0.32         |
| Portugal          |           |          |                         |              |
| National IAQ      | 500       | 500      | 100                     |              |

The data obtained from the measurements of the chemical indicators concentrations in the selected rooms are shown in Table 6. It should be remarked that these measurements were carried out with no effective occupants in the rooms; therefore the CO₂ values are not valid for compliance verification purposes.

3.3. Biological indicators

The recommended threshold value for total concentration of bacteria and fungi in the indoor air is 500 CFU/m³ in Portugal [14]. As for Legionella, the maximum limit value is 100 CFU/L of water, the sampling criteria being defined in the technical note NT-SCE-02 [17], regarding namely the minimum number of samples and the typically recommended collection points in the hot-water ductwork. In the present audit, besides the purge of the hot-water storage tank and the return collector, 1 L samples were collected from ten showers (in rooms selected randomly), plus one at each of the staff male and the female washrooms. The measured data for selected rooms are shown in Table 7 and these results indicate that the indoor air microbial pollution in guest rooms is well below the limit values. However, a generalized contamination by Legionella was detected in the hot-water circuit, although with no presence of the pathogenic species (Legionella pneumophila). This imperatively determined an immediate overall thermal decontamination procedure, of which the effectiveness was checked out by further water sampling and analysis two weeks later.

3.4. Discussion

In the course of this audit, some problems or situations with risk for good IAQ in the hotel building were identified, such as: (1) excessive CO₂ concentration in the guest rooms during the period of occupancy (insufficient ventilation); (2) too high particle concentration in some rooms (after the housekeeping operation), due to dispersion of dust deposited on carpets; (3) contamination by non-pathogenic Legionella of the sanitary hot-water circuit; (4) signs of fungi growing on the inner surface of a wall (due to infiltrations); (5) degradation of the inner wall insulation, of the condensate tray and of the filter cassettes of the main AHU1 (serving the lobby, the reception and other spaces at the level 0) and poor hygienic conditions due to inefficient filtration of the outdoor air; (6) Poor filtration effectiveness in all AHUs; (7) Deterioration and dirtiness in the condensate trays of the rooms fan coil units, due to bad drainage and difficult access for maintenance.

| Location          | Total bacteria (CFU/m³) | Total fungi (CFU/m³) | Legionella (CFU/L water) |
|-------------------|------------------------|---------------------|-------------------------|
| Suite #320        | 131                    | 6.5                 | 2271                    |
| Suite #620        | 140.5                  | 3.5                 | 236                     |
| Portugal national | 500                    | 500                 | 100                     |
| IAQ guideline     |                        |                     |                         |
These findings led to a set of recommendations for improvement of IAQ conditions, namely:

1. Keep the mechanical exhaust fan of the bathrooms working during the night period (to guarantee a minimum level of outdoor air intake by infiltration);
2. Improve the methodology and increase the frequency of cleaning/washing the room carpets;
3. Retrofit of the sanitary hot-water network with stainless steel ducts;
4. Retrofit some parts of the building envelope, to prevent water infiltration and condensation on the inner surfaces;
5. Install an efficient filtration section at the fresh air intake of the smaller AHUs;
6. Replace the AHU1 by a new one, with energy recovery, efficient filtration, a plug fan and the possibility of variable, demand controlled air flow rate;
7. Replacement of the condensate trays of FCUs.

It is necessary to state that according to the energy certification of building program in Portugal, the analyzed hotel building is categorized as “A” class. However, as it was documented above, there are some problems related to the indoor air quality in the building. Fortunately in Portugal it is mandatory to have IAQ audit along with the energy certification of large buildings. Thus the building manager was mandated to solve the reported IAQ problems. Finally, the building manager was sensitized for the importance of guaranteeing good IAQ in the building, which depends greatly on the adequate operation and planned maintenance of the HVAC systems.

The result from IAQ audit shows the necessity and the convenience of performing an IAQ audit along with the energy audit of buildings.

4. Conclusion

Hotel buildings are expected to fulfill a variety of requirements, applicable codes and standards, and environmental and community impact rules. Among these requirements, IAQ is typically addressed through compliance with only minimum code requirements, which are based on industry consensus standards. Yet IAQ affects occupant health, comfort, and productivity, and in some cases even building usability, all of which can have significant economic impacts for building owners/managers and occupants/guests.

While hotel manager/owner and building professionals may recognize the importance of IAQ, they often do not acknowledge how design, construction decisions and control routines can result in IAQ problems. In addition, they may assume that achieving a high level of IAQ is associated with premium costs and novel or even risky technical solutions. In other cases, they may employ individual measures thought to provide good IAQ, such as increased outdoor air ventilation rates or specification of lower emitting materials, without a sound understanding of the project-specific impacts of these measures or a systematic assessment of IAQ priorities. On the other hand little research has been concerned to the IAQ of hotel buildings up to now.

This study presented practical information and guideline on how to establish and conduct the comprehensive IAQ audit approach for hotel buildings, based on Portugal national laws. The procedure presented for IAQ audit of hotel buildings proved to be simple and comprehensive. Beyond the preliminary visit, the systematic approach involves the measurement of physical parameters, the monitoring of the concentrations of selected indoor air pollutants, and the measurements of airborne fungi and bacteria. Continuous monitoring of metabolic CO$_2$ revealed to be a useful method to have a better knowledge of the AER in the studied space and to check the effectiveness of the implemented corrective measures.

In particular, the application of the procedure to a selected hotel building enabled to survey the IAQ performance of the hotel building. The conclusion is that such a methodology is suitable for short period assessment on hotel building stock, being very useful for finding the appropriate remediation actions to solve the IAQ problems in such buildings. Moreover, the results demonstrated the feasibility of the approach, thus encouraging further extensions and/or improvements and application to other building types, such as office buildings and schools.

References

[1] Kuo N-W, Chiang H-C, Chiang C-M. Development and application of an integrated indoor air quality audit to an international hotel building in Taiwan. Environmental Monitoring and Assessment 2008;147:139–47.
[2] Chan W, Lee S, Chen Y, Mak B, Wong K, Chan C-S, et al. Indoor air quality in new hotels’ guest rooms of the major world factory region. International Journal of Hospitality Management 2009;28:26–32.
[3] Bohdanowicz P, Martincic IM. Thermal comfort and energy saving in the hotel industry. In: Paper presented at the AMS 15th conference on biometeorology and aerobiology & 16th international congress on biometeorology. Kansas City; 2002.
[4] Bohdanowicz P, Martincic I. Determinants and benchmarking of resource consumption in hotel buildings: a study of Hilton International and Scandic in Europe. Energy and Buildings 2007;39:82–95.
[5] Rada J. Designing and building eco-efficient hotels. Green Hotelier: Magazine of the International Hotels Environmental Initiative 1996;4:10–1.
[6] Teeters K, Jones T, Boatinan JF. The future of indoor air quality: legal and economic implications. Cornell Hotel and Restaurant Administration Quarterly 1995;36(2):43–9.
[7] Lane G, Ferrari A, Dreher HM. Legionnaire’s disease: a current update. Medscape Nursing 2004;13:409–14.
[8] Radun D, Niedrig M, Ammon A, Stark K. SARS: retrospective cohort study among German guests of the Hotel ‘M’, Hong Kong. European Communicable Disease Bulletin 2003;9:229–30.
[9] Li Y, Huang X, Yu I, Wong T, Qian H. Role of air distribution in SARS transmission during the largest nosocomial outbreak in Hong Kong. Indoor Air 2005;15:83–93.
[10] European Union. On the Energy Performance of Buildings. Directive 2002/91/EC of the European Parliament and of the Council. Official Journal of the European Communities, Brussels December, 2002.
[11] Cen EN 15251. Indoor environmental input parameters for design and assessment of energy performance of buildings-addressing indoor air quality, thermal environment, lighting and acoustics. Document for formal vote; 2006.
[12] Olesten BW. The philosophy behind EN15251: indoor environmental criteria for design and calculation of energy performance of buildings. Energy and Buildings 2007;39:740–9.
[13] Decreto-Lei no 78/2006 de 4 de Abril. Publicado no Diário da República, I Série-A, No 67. Aprova o Sistema Nacional de Certificação Energética e da Qualidade do Ar Interior nos Edifícios.
[14] Decreto-Lei no 79/2006 de 4 de Abril. Publicado no Diário da República, I Série-A, No 67. Aprova o Regulamento dos Sistemas Energéticos de Climatização em Edifícios.
[15] Decreto-Lei no 80/2006 de 4 de Abril. Publicado no Diário da República, I Série-A, No 67. Aprova o Regulamento das Características de Comportamento Térmico dos Edifícios.
[16] Cheong KW, Chong KY. Development and application of an indoor air quality audit to an air-conditioned building in Singapore. Building and Environment 2001;36:181–8.
[17] Technical Note NT-SCCE-02 (2009), “Metodologia para auditorias periódicas de QAI em edifícios de serviços existentes no âmbito do RSECE” (versão provisória). Agência para a Energia – ADENE.
[18] ASHRAE. ASHRAE handbook-HVAC applications. USA: American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc.; 1999.
[19] ISO 16000-1: 2004 (E). Indoor air quality – Part 1: Infiltration and Ventilation for Buildings and Structures. International Organization for Standardization; 2004;1(1):39–44.
[20] Godwin C, Battenman S. Indoor air quality in Michigan schools. Indoor Air 2007;17:109–21.
[21] Coley Bersteiner. Carbon dioxide levels and ventilation rates in schools. Educational facilities journal 1995;36:181–8.
[22] Charlesworth PS. Air exchange rate and airtightness measurement techniques – a review. Proceedings of the 4th international conference on Air Infiltration and Ventilation Centre; 1988.
[23] Naydenov K, Barankova P, Sundell J, Melikov AP. Proceedings of the 9th international Conference on Air Distribution in Rooms – ROOMVENT 2004, 5–8 September, Coimbra, Portugal. Distribution of carbon dioxide produced by people in a room: part 1 – field study; 2004.