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A Humanoid Social Robot Based Approach for Indoor Environment Quality Monitoring and Well-Being Improvement

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Abstract

The indoor environmental quality (IEQ) monitoring inside buildings where people spend most of their time is essential for ensuring their well-being. Traditional approaches based on Building Automation and Control Systems consider buildings equipped with many different sensors. Unfortunately, the sensors are not always placed for taking the measurements at the right positions. Besides, users could feel a negative perception due to continuous supervision. The present work proposes an approach based on a social humanoid robot that monitors indoor environmental quality. It friendly interacts with occupants providing appropriate suggestions. Particularly, the social robot has been endowed with cognitive capabilities that ground on (i) a proper ontology that formalizes the IEQ domain, (ii) on formal definitions of normative standards based on deontic logic, and (iii) on algorithms for reasoning about the compliance of the environment with the normative standards. The proposed approach has been experimentally verified in some offices of the National Research Council of Italy located in Palermo, and it has involved ten participants. It is worth noting that at the end of the measurement campaign appears that in some cases, compliance with the standard does not imply the user's well-being and vice versa.

Keywords Social robotics · Comfort indoor · Human-centric approach · Norm-based system

1 Introduction

Indoor environmental quality (IEQ) is considered a relevant factor for the health, comfort and performance of individuals, also considering that, in the advanced areas of the planet, people spend most of their time inside buildings [11,32]. The concept of IEQ is huge and depends on many variables such as temperature, relative humidity, the concentration of pollutants, noise, lighting. These parameters can be grouped into four significant areas that define the IEQ [2]: Thermal, Visual, Acoustic and Hygienic comfort. Several researchers established that the quality of the indoor environments has a direct effect on the life of the occupants. Living in buildings with poor indoor environmental quality may cause serious health problems. Among these, there are allergic reactions to indoor pollutants due to poor air quality, vision difficulties caused by poor lighting, blood circulation problems for high temperatures, and so on [3,15]. Moreover, some studies demonstrated that discomfort into the indoor environment could lead to a significant reduction in work performance of occupants [14]. Thus, several standards have been proposed for dimensioning buildings and plants for ensuring comfort conditions, such as UNI EN 15251 [31], ASHRAE 55-92 [28], EN 12464-1 [29]. A well-known method for achieving comfort conditions is to use a Building Automation and Control System (BACS) that collects data about the state of the physical environment and residents and takes actions opportunely [12]. Traditionally, such data are collected using a dense array of sensors in every building location to be monitored. However, there are many issues to be considered using such an approach. First of all, it is expensive, principally when it has to be implemented in existing old buildings. It may require a complex integration process for sensors as well as maintenance and calibration processes. Moreover, some studies [5,7] demonstrated that the wrong location of the sensors could decrease the perfor-

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mance of a BACS. As a consequence, data should be acquired by locating the sensors in specific positions. However, this is not always possible. For example, parameters such as the illuminance or the radiant temperature have to be captured close to the human. Recent studies [20] demonstrated that commonly building occupants prefer to switch off the automatic mode of the system. Several reasons are underpinning such a choice. The main reason is that individuals want to have a sense of control, above all when the adjustment performed by the system is not in line with their current needs or when the reasons for the automatic change is not clear for the individual. For example, office workers prefer daylight in their office and enjoy to view the external world thus they do not appreciate automatic blinds systems that decide to close the curtains to be compliant with the quality standard of illuminance.

For the above mentioned reasons, social robotics is receiving considerable attention from the scientific community for its great potential in improving the acceptance of robotic systems in daily life. Social robots are designed to interact with humans naturally and to engage them to a cognitive level and an emotional level to provide adequate social and task-related support to people [27]. It has been experimented that an individual is commonly more influenced and engaged by the interactions with an embodied physical agent compared to other technologies [4,17,19,22,25,26].

Moreover, recent studies demonstrated that the indoor environment quality depends not only on variables related to physical boundary parameters (such as humidity, noise, lighting, temperature) but also on non-measurable factors (such as psychological and physiological ones). The method called *Post Occupancy Evaluation* (POE) has been developed to capture also such aspects [10]. It is mainly based on a questionnaire appropriately formulated [9].

The novel idea of this paper consists on attributing to a social humanoid robot the task to monitor the indoor environmental quality by (i) acquiring physical parameters of the environment, (ii) performing an appropriate POE survey for obtaining user's preferences and perceptions, (iii) verifying the compliance with the standards of comforts, and (iv) giving suitable suggestions to the occupants for improving their well-being.

Such an approach allows mitigating the issues arisen by the adoption of traditional approaches, thus obtaining further advantages. In particular, the need for instrumenting different locations of the building with a set of sensors is eliminated by endowing the robot with a kit of external sensors, thus reducing costs and effort for installation. Moreover, both the ability of the robot to move close a person for gathering data at the right position and the ability to engage conversation for capturing human preferences improve the analysis of the real state of the comfort of the individual. Finally, a common situation is that often an individual acquires bad habits during its daily life such as working with a brightness level too low which could damage his/her eyesight or taking the temperature too high that may cause, for example, loss of concentration and of ability to perform a mental task. In this work, we also exploit the social abilities of the robot for sensitizing the user towards a correct behaviour. It is obtained giving suggestions to improve his/her comfort demanding to the user the final decision.

To achieve our aims, the proposed approach mainly grounds on: (i) a semantic representation of data through formal models (i.e., ontology); (ii) normative system models based on deontic logic, and (iii) methods for determining the conformity to the existing normative. Hence, the main contributions of this paper are:

1. The definition and the implementation of an IEQ Ontology, which conceptualizes not only the physical environmental parameters but also user's features and preferences as well as his/her perception about what (s)he senses in his/her environment;
2. A formal definition of normative standards;
3. The definition of algorithms for reasoning about the compliance of the environment with the normative standards;
4. The implementation on a social robotic platform of (i) capabilities to acquire data from external sensors; (ii) capabilities to retrieve knowledge about the context; (iii) social abilities to perform the post-occupancy evaluation questionnaire for gathering user preferences; (iv) a normative compliance reasoner and (v) abilities to give suggestions.

We experimented the proposed approach with ten researchers working in the offices of the National Research Council of Italy located in Palermo.

The rest of the paper is organized as follows. Section 2 poses the work in Literature. Section 3 gives an overview of indoor environmental comfort. Sections 4 and 5 introduce the proposed ontology for Indoor Environment Quality and the algorithms for reasoning about the compliance with the standards. Section 6 shows the architecture of social robots for evaluating IEQ. Section 7 presents a case study related to working environments and discusses the results. Finally, in Section 8 conclusions and future works are presented.

2 Related Work

Building Automation and Control Systems [12] represent a traditional way to achieve comfort conditions. A BACS refers, in the broadest sense, to a centralised system that monitors, controls, and records the functions of building service systems. It can improve the environmental impact and user well-being.

Several studies in the literature highlighted some issues arising from their employment. One of these issues concerns the correct location in which a sensor has to be placed to take the appropriate measurements. Commonly, it is difficult to install the sensors in specific locations due to the layout of the environment or some wiring constraints. Some works proved that the location of the sensors could decrease the performance of a BACS. [5,7]. A second issue is related to the general apprehension caused by the autonomous control that such systems have on the facilities of the environment. Recent studies [20] demonstrated that commonly occupants prefer to switch off the automatic mode of the system. Additionally, recent researches in the field of social robotics highlighted that the anthropomorphic and physical nature of a social robot positively affects human engagement increasing empathy [4,17,19,22,25,26]. To cite a few, in [22], authors investigated the user's behaviour in accepting suggestions given by a humanoid robot compared to a computer agent. The results of the study showed that a physical robot is more effective in providing recommendations. In [4], authors studied the capabilities of a robot to persuade human users, compared to a virtual agent, showing increased confidence and trust for the physical robots.

In [25], authors compared the use of a humanoid robot with a mobile application for providing recommendations. The main result was that users prefer a social robot. In [26], the role of the robot appearance concerning the acceptance of recommendations was investigated. In particular, different humanoid robots were used to give advertisements to shopping mall customers. Such a study proved that small robots attract people since the users interacted easily with them.

Hence, the novel idea of this paper is to assign to a social humanoid robot the task to monitor the indoor environmental quality and to give appropriate suggestions to the occupants for improving their well-being. To the best of our knowledge, only Mantha et al. [18] employed a mobile robot (i.e., a turtle-bot) for collecting environmental data in existing buildings with the final purpose to achieve an optimal building retrofit (e.g., energy saving).

Conversely, the approach we propose focuses on human well-being according to the normative standards. Leading the environment in a state compliant with the standards allows not only to achieve human comfort but also to avoid waste of energy. Moreover, the use of a social robot allows capturing both measurable parameters (i.e., the environmental data) and not directly measurable factors (i.e., psychological and physiological ones). These latter elements are necessary for making personalised and comfortable environments.

Moreover, the approach proposed Mantha et al. acquires data only on the upper surface of the robot, because the sensors are placed on the head of the turtle-bot. It is in contrast with some normative standards for human comfort. These shreds of evidence show that our proposed approach differs from the Mantha's approach both for the method and the purpose.

In the following, some details about the indoor environmental quality are provided.

3 Overview on Indoor Environmental Quality

The environmental quality in a building refers to different fields of environmental comfort. An important issue is to understand what are the elements that determine the comfort perception of individuals. The concept of comfort is quite vague because it is strictly related to our perception of the world through our five senses: touch, sight, hearing, smell, and taste. Each of them can lead an individual to perceive a certain degree of comfort. In [13] was shown that the primary contribution to IEQ satisfaction is linked to four kinds of comfort:

- *Thermal Comfort* Temperature is the most significant component that influences the experience of comfort in a space. Our body performs within an internal temperature range narrower than the external temperature. Our metabolism generates heat that needs to be dissipated toward the surrounding air. When the external temperature is high, this process becomes quite hard, and we may perceive warm. Conversely, when the external temperature is low, the rate of heat loss becomes more rapid, and we may feel cold. Also, the relative humidity contributes to the sense of thermal comfort. During icy winters, high levels of relative humidity produce a more considerable sensation of cold. On the contrary, in hot environments, high levels of humidity impede the cooling effects due to the sweating, thus leaving the body prone to over-heating.
- *Visual comfort* Visual comfort is related to the intensity and quality of the light within a given space at a given time. Light is a fundamental element in our capacity to see. Both scarce and exaggerate light levels can cause visual discomfort. Visual comfort mainly depends on photometric quantities such as the illuminance (i.e., the amount of luminous flux per unit area). Moreover, it also encompasses other aspects, such as the view of outside connected to nature, the light quality, and the absence of glare.
- *Acoustic comfort* It is the well-being of occupants about the acoustic environment. Providing acoustic comfort consists of minimizing noise and maintaining satisfaction among residents. Acoustic comfort helps to improve concentration and enables better communication.
- *Hygienic comfort* The hygienic comfort is related to air quality, considering the concentrations of pollutants in an environment and the capacity to refresh the air. Several

Table 1 Comfort zones for summer and winter seasons

Relative humidity (%)	Summer		Winter	
	Low temp (°F)	High temp (°F)	Low temp (°F)	High temp (°F)
30	76	82	69	78
60	74	78	68	75

negative impacts, ranging from coughs or headaches to severe illness, can be caused by poor air quality.

Hence, while the discomfort is experienced when we are approaching extreme values of the parameters, the comfort is primarily related to determining their ranges of acceptability. Various standards have been proposed for establishing these ranges.

In particular, the standard ASHRAE 55-92 [28] provides the recommended values of the parameters responsible for thermal well-being. Table 1 shows the comfort zones during winter and summer seasons according to the relative humidity.

It is worth noting that human beings are sensitive to slight temperature changes. However, they are not perceptive to differences in relative humidity levels within the range of 30% and 60%, which is the primary reason that this range is often cited as the baseline. Moreover, it is well-known that different tasks, activities and types of indoor environment require a different level of illuminance for achieving visual comfort. For this reason, the European standard EN 12464-1 [29] defines lighting requirements for indoor work areas in terms of quantity and quality of illumination according to the particular task and space. It covers offices, places of public assembly, restaurants/hotels, theatres/cinemas. Table 2 shows an excerpt of the recommended light levels for offices according to the task performed by the occupant.

Noise Ratings (NR) [6] is the standard to measure and specify noise in buildings and occupied spaces. Noise Rating curves were developed by the International Organization for Standardization (ISO). They define the acceptable indoor environment for hearing preservation, speech communication and annoyance. Sound pressure levels depend on room type and its use, covering a variety of locations from concert halls, lecture rooms and offices. Table 3 shows an excerpt of the recommended NR levels for some application areas. Noise Rating Curves [6] shows the mapping of NR levels with the most common unit for measuring sound pressure level, the dB level. For example, the maximum sound pressure level for spaces with office end-use is 55 dB.

The above-mentioned standards provide a set of conventions and indices, such as PMV and PPD [30], that can be regarded as targets, but the experience of comfort, however, remains a product of our senses. It is essential to underline that each occupant can have a different perception of the

Table 2 Examples of recommended light levels for offices

Type of activity	Illuminance (lx)
Writing, typing, reading …	500
Technical design	750
Conference and meeting	500
Reception	300

Table 3 The highest recommended noise rating levels

Type of application	Max noise rating level
Concert halls, broadcasting and recording studios, churches	NR 25
Halls, shops cloakrooms, restaurants, night clubs, offices,	NR 40
Offices with business machines, typing pools	NR 50
Foundries and heavy engineering works	NR 70

environmental parameters, different needs and preferences. In general, it depends on user's factors such as age, gender and pathology.

It is essential to understand the impact of IEQ conditions on each occupant's satisfaction by integrating actual IEQ data with simultaneously acquired survey information. For this reason, the method called *Post Occupancy Evaluation* has been developed to capture also psychological and physiological aspects that influence environmental comfort. POE is a method for evaluating the performance of a building [10]. It can be conducted while the occupant is in the space as long as the user stays for a certain period in that space.

The POE method analyses the objective measurements and subjective elements of IEQ from four points of views [33]: thermal, air quality (CO_2), visual and acoustic perspective. User's satisfaction surveys are mainly prepared for understanding how much occupants are satisfied by their indoor environment. These surveys may include questions regarding, not only IEQ elements, but also spatial characteristics, functionality, and satisfaction beyond the environmental factors.

In this study, we focus on three types of comfort: visual, thermal and acoustic. Moreover, the POE questionnaire is built based on existing ones. In the next section, an IEQ ontology formalizes such domain.

4 Indoor Environmental Quality Ontology

A significant issue for social robots is the execution of complex tasks in real environments and the ability to analyse relevant situations for the target application. It often implies a formalisation of the sphere of knowledge in which the robot operates. It is especially necessary for the evaluation of comfortable environments that depends on several factors. Indeed, the Indoor Environmental Quality is influenced by complex interactions of several different phenomena (including weather and indoor activities of occupants), by features of the building itself (e.g., the number and size of windows, the type of light) and also by user's features and preferences as well as his/her perception about what (s)he senses in his/her environment. Moreover, for establishing a relationship between the knowledge of the state of the world within a robot works and the normative framework (i.e., standards) regulating the IEQ, it is necessary to refer to the same semantic layer. This requirement can be satisfied by adopting a knowledge formalization based on a proper domain ontology. Domain ontologies are descriptions of classes of concepts and relationships among concepts that describe an application area, meaning the indoor environmental quality in our study.

A reduced IEQ ontology is presented in [1], which focuses only on the features of the environment. The approach proposed in this work mainly focused on the human, considering his/her well-being according to the normative standards. Hence, we designed and implemented an extended ontology for indoor environmental quality evaluation that conceptualizes, beside the real measurements of the physical environmental parameters, also the user features, his/her preferences and perceptions of the environment along with the standard recommendations defined for IEQ.

Figure 1 shows the concepts and relationships of the proposed IEQ ontology. It consists of three parts that ground around three main concepts: *Occupant*, *Environment* and *Recommendation*.

The former contains information about the Occupant (i.e., the person situated in the environment) along with his/her features (such as age, gender, role, pathologies, etc…), preferences (such as the temperature and the illuminance level), and perceptions about internal and external conditions (such as the general status and the perceived heat). Table 4 shows an excerpt of attributes and relationships of the ontological class *Occupant*.

For the case under study in this paper, we introduced the class *Employee* (Table 5).

It is a characterization of an occupant with specific attributes (e.g., the time (s)he usually spends at work) and relationships (e.g., where (s)he works) along with those inherited from the *Occupant*.

To capture how an occupant perceives the environment (s)he lives in, we introduced the ontological concept *User_Perception*. The *User_Perception* is defined as the person's awareness about something through the senses. Some kinds of user perception included in the ontology are perceptions about environmental parameters such as heat, loudness and air flux. For example, Table 6 shows the ontological class regarding heat perception. The *Heat_Percept* defines the situation at a particular time perceived by an individual about the temperature, for example, (s)he could feel hot, slightly warm or cold.

Conversely, for acquiring user preferences, we introduced the ontological concept *User_Preference*. A user preference defines the greater liking of the occupant for one alternative over another or others. An occupant may express preferences about some elements such as temperature, illuminance and humidity. For example, Table 7 shows the ontological class regarding illuminance preference. The *Illuminance_Preference* represents how the individual would prefer the illuminance level with respect to the current illuminance among the alternatives: *darker*, *brighter*, and *it is ok*.

The second part of the ontology contains information about the environment. In particular, the environmental parameters (such as humidity, sound level, and plane illuminance) that characterize in a given moment the environment under study. In our ontology, an environment is defined as the area and the surroundings in which a person lives or operates with its environmental parameters. For the scope of this paper, we focused on an indoor environment that is an environment located inside an indoor area (see Table 8).

For the case study, Table 9 shows the ontological class that defines a job area, which is an indoor environment where employees perform their job activities.

Finally, the latter part of the ontology provides concepts and relationships for evaluating the IEQ. In particular, it highlights what elements influence the IEQ (i.e., *Thermal*, *Acoustic*, *Visual* and *Hygienic Comfort*[1]) and the recommendations that should be followed for improving the IEQ. Specifically, in our ontology, a recommendation is a suggestion that something is right or suitable for a particular purpose or job. Thus, we model the comfort standards as a recommendation.

In particular, *Thermal Comfort Standards* are statements about recommended values of relative humidity and temperature responsible for the thermal well-being. *Acoustic Comfort Standards* are recommended values of max noise level acceptable for human hearing. *Visual Comfort Standards* are statements about recommended light levels acceptable for visual well-being. Table 10 shows the features of the onto-

[1] Hygienic Comfort is introduced for completeness of the ontology, although it is not addressed in this paper.

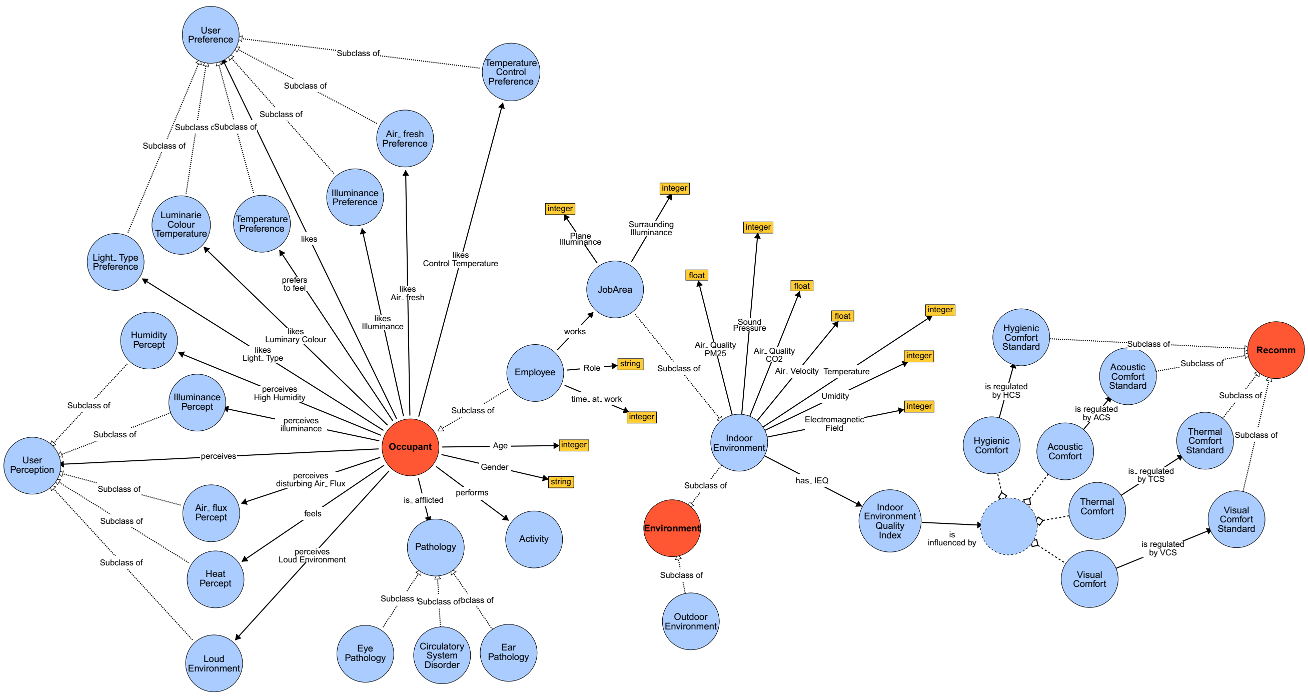

Fig. 1 The indoor environmental quality ontology

Table 4 Elements of the ontological class *Occupant*

CLASS: OCCUPANT
Attributes:

Name: the name of the occupant.
Age: the age of the occupant.
Gender: the gender of the occupant.

Relationships:

is_afflicted_by: *(Domain)* Occupant - -> *(Range)* Pathology
performs: *(Domain)* Occupant - -> *(Range)* Activity
perceives: *(Domain)* Occupant - -> *(Range)* User_Perception
perceives_Loud_Environment *SubPropertyOf perceives:*
(Domain) Occupant - -> *(Range)* Loud_Environment_Percept
perceives_disturbing_Air_Flux *SubPropertyOf perceives:*
(Domain) Occupant - -> *(Range)* Air_Flux_Percept
feels *SubPropertyOf perceives:*
(Domain) Occupant - -> *(Range)* Heat_Percept
likes: *(Domain)* Occupant - -> *(Range)* User_Preference
prefers_to_feel *SubPropertyOf likes:*
(Domain) Occupant - -> *(Range)* Temperature_Preference
likes_Air_Fresh *SubPropertyOf likes:*
(Domain) Occupant - -> *(Range)* Air_Fresh_Preference
likes_Colour_Temperature *SubPropertyOf likes:*
(Domain) Occupant - -> *(Range)* Temperature_Colour_Preference
likes_Humidity_Level *SubPropertyOf likes:*
(Domain) Occupant - -> *(Range)* Humidity_Preference
…

Table 5 Attributes and relations of the class *Employee*

CLASS: EMPLOYEE **Attributes:**
Role: the role assumed by the employee at work ***Time_at_work:*** the time usually spent by the employee at work ***Attributes inherited from*** Occupant
Relationships:
SubClassOf: Occupant ***works:*** (Domain) Employee - -> (Range) Job_Area ***Relations inherited from*** Occupant

Table 6 Relationships of the class *Heat_Percept*

CLASS: HEAT_PERCEPT **Attributes:** **Relationships:**
SubClassOf: User_Perception **feels** SubPropertyOf perceives: (Domain) Occupant - -> (Range) Heat_Percept

Table 7 Relationships of the class *Illuminance_Preference*

CLASS: ILLUMINANCE PREFERENCE **Attributes:** **Relationships:**
SubClassOf: User_Preference ***likes_Illuminance*** SubPropertyOf likes: (Domain) Individual - -> (Range) Illuminance_Preference

Table 8 Elements of the class *Indoor Environment*

CLASS: INDOOR ENVIRONMENT **Attributes:**
Sound Pressure Level: the sound pressure of a sound relative to a reference pressure measured in units of decibels (dB). The reference sound pressure is typically the threshold of human hearing. Loud soundshave high sound pressure level. ***Temperature:*** the degree or intensity of heat present in the environment expressed in terms of Celsius scale. ***Relative_Humidity:*** the amount of water vapour present in air expressed as a percentage of the amount needed for saturation at the same temperature. ***Air Velocity:*** the rate of air movement at a point.
Relationships:
SubClassOf Environment ***has_IEQ*** (Domain) IndoorEnvironment - -> (Range) Indoor_Environmental_Quality_Index

Table 9 Attributes and relationships of the class *Job Area*

CLASS: JOB AREA **Attributes:**
Plane Illuminance: the total luminous flux incident on the working surface ***Surrounding_Illuminance:*** The illuminance of the area adjacent to the visual task area ***Attributes inherited from*** Indoor Envarionment
Relationships:
SubClassOf IndoorEnvironment ***Relations inherited from*** IndoorEnvironment

Table 10 Elements of the ontological classes *Indoor Environmental Quality Index*, *Thermal Comfort* and *Thermal Comfort Standard*

CLASS: INDOOR_ENVIRONMENTAL_ QUALITY_INDEX **Attributes:** **Relationships:**
has_IEQ: *(Domain)* IndoorEnvironment - -> *(Range)* Indoor_Enviraonmental_Quality__Index **is_influenced_by:** *(Domain)* Indoor_Environmental Quality_Index - -> *(Range)* Visual_Comfort, Acoustic Comfort, Hygienic Comfort, Thermal_Comfort
CLASS: THERMAL_COMFORT **Attributes:** **Relationships:**
is_influenced_by: *(Domain)* Indoor_Environmental_Quality_Index - - > *(Range)* Thermal_Comfort ***is_regulated_by_TCS:*** *(Domain)* Thermal_Comfort - -> *(Range)* Thermal_Comfort _Standard
CLASS: THERMAL_COMFORT_STANDARD **Attributes:** **Relationships:**
SubClassOf Recommendation ***is_regulated_by_TCS:*** *(Domain)* Thermal_Comfort - -> *(Range)* Thermal_Comfort _Standard

logical elements *IEQ Index*, *Thermal Comfort* and *Thermal Comfort Standard*.

The ontological elements describing the *Environment* part are used from the robot for identifying un-compliant situations with the recommendations that may negatively influence the individual perception of environmental comfort. On the other hand, the elements characterising the occupant such as his/her preferences and perceptions allow the robot to understand if the conformity to the standards truly represents healthy and comfortable situations for the occupants, thus providing personalised suggestions. Trivially, an environment compliant with the visual comfort standards could be perceived by an individual with some eye pathology as uncomfortable.

The following section presents the algorithm for reasoning about the compliance of the environment with the normative system.

5 Algorithm for Evaluating the Compliance to the IEQ Standards

The algorithm for evaluating the compliance of the environment with the standards dealing with the indoor environmental quality is based on the theoretical framework proposed in [21]. In such a framework, norms are conceptualised adopting a typical system of deontic logic that comprises ordinary first-order logic and some deontic operators. In this work, we considered only the weak operators such as recommended and discouraged. Thus, to make all the approach consistent, we also chose the formalism of first-order logic as a form of knowledge representation to be used by robots for performing normative reasoning. First-order logic allows to describe the domain of interest as consisting of objects, i.e., things that have an individual identity, and to construct logical formulas around these objects formed by predicates, functions, variables and logical connectives.

Hence, a *state of the world* represents a set of declarative information about events occurring in the environment and relations among events at a specific time. It is formally defined as follows.

Definition 1 (State of the world) Let $\mathcal{D}$ be the set of concepts defining a domain. Let $\mathcal{L}$ be a first-order logic defined on $\mathcal{D}$ with $\top$ a tautology and $\perp$ a logical contradiction, where an atomic formula $p(t_1, t_2, \ldots, t_n) \in \mathcal{L}$ is represented by a predicate applied to a tuple of terms $(t_1, t_2, \ldots, t_n) \in \mathcal{D}$ and the predicate is a property of or relation between such terms that can be true or false. A *state of the world* in a given time t ($\mathcal{W}^t$) is a subset of atomic formulae whose values are true at the time t:

$$\mathcal{W}^t = [p_1(t_1, t_2, \ldots, t_h), \ldots, p_n(t_1, t_2, \ldots, t_m)]$$

In this work, $\mathcal{D}$ coincides with the concepts defined in the Indoor Environment Ontology, $p(t_1, t_2, \ldots, t_n) \in \mathcal{L}$ represents a relation in terms of logical sentences about objects of IEQ. As a consequence,

$$\mathcal{W}^t = [p_1(t_1, t_2, \ldots, t_h), \ldots, p_n(t_1, t_2, \ldots, t_m)]$$

coincides with the the first-order logic representation of the Indoor Environment Ontology instances.

It is worth noting that Definition 1 is based on the close world hypothesis [24] that assumes all facts that are not in the state of the world are considered false.

Another key element to be formally defined is the concept of normative standards that we model using deontic logic. Deontic logic is a branch of logic concerning the reasoning about norms. In particular, as we previously said, such standards define recommendations for improving the comfort of the indoor environments. Hence, we define the concept of recommendation starting from the concept of norm defined in [21] and introducing the weak operators *recommended* (R) and *discouraged* (D) of the deontic logic [16].

A *Recommendation* is a statement that something would be good or suitable for a particular job or purpose. In other words, a suggestion about the best state of affairs that leads to improving something (the goal of the recommendation). It is formally defined as follows.

Definition 2 (Recommendation) Let $\mathcal{D}$, $\mathcal{L}$, and $p(t_1, t_2, \ldots, t_n)\in\mathcal{L}$ be as previously introduced in the Definition 1. Let $\phi\in\mathcal{L}$ and $\rho\in\mathcal{L}$ be formulae composed of atomic formula by means of logic connectives AND ($\wedge$), OR ($\vee$) and NOT ($\neg$). Moreover, let $D_{weak-op} = \{recommended, discouraged\}$ be the set of the weak deontic operators. A *Recommendation* is defined by the elements of the following tuple:

$$n = \langle r, g, \rho, \phi, d\rangle_{[scope]}$$

where: *scope* identifies the field of reference of the recommendation; r is the Role the recommendation refers to; g is the Goal the recommendation refers to; $\rho\in\mathcal{L}$ is a formula expressing the state of affairs that is recommended or discouraged by the recommendation; $\phi\in\mathcal{L}$ is a logic condition (to evaluate over a state of the world $\mathcal{W}^t$) under which the recommendation is applicable; $d \in D_{weak-op}$ is the weak deontic operator applied to ρ.

A recommendation indicates to someone, playing the role r, that, for achieving the goal g in the state of the world $\mathcal{W}^t$, it is advisable that

$$\begin{aligned}&(i) \quad \rho(\mathcal{W}^t) = true \quad \text{if } d = recommended\\&(ii) \quad \rho(\mathcal{W}^t) = false \quad \text{if } d = discouraged\end{aligned}$$

when the applicability condition ϕ is verified. If the statement representing the applicability condition results in a tautology, the recommendation is applicable in each state of the world.

Starting from these definitions, the algorithm (see Algorithm 1) for evaluating the compliance to recommendations results to be straightforward. It is based on verifying the conditions (i) or (ii) aforementioned.

In the next section, we show an implementation of the algorithm in Bordini and Hübner [8], which is a Java-based interpreter of a BDI language.

Algorithm 1: Compliance to Recommendations

```
Data: W^t, R
for j ← 1 to size(R) do
    ⟨r, g, ρ_j, φ_j, d_j⟩[scope] ← n_j
    if φ_j(W^t) = true ∨ φ_j = ⊤ then
        if ( d = Recommended) then
            d_ρ = ρ_j
        if ( d = Discouraged) then
            d_ρ = ¬ρ_j
        if d_ρ(W^t) = true then
            Compliance(n_j) = true
    else
        Compliance(n_j) = false
```

6 A Social Robot for Evaluating Indoor Environmental Quality

A primary goal of this work is the design of a social robot able to evaluate the environmental quality of the indoor area where people spend a significant part of their time and to give suggestions according to user preferences and perceptions for improving their well-being. Such a robot was developed for conducting monitoring campaigns. Each monitoring campaign is composed of many sessions, corresponding to people to be monitored. For this purpose, the robot was endowed with:

– The capabilities to interact with a user to capture the preferences and perceptions about the environment (s)he lives in;
– The abilities to acquire environmental parameters from external sensors;
– The knowledge about the standard recommended values for human comfort in indoor environments;
– Reasoning capacities for evaluating the compliance with the environmental quality standards for human well-being;
– Finally, the capability to give appropriate suggestions according to the particular situations that can occur.

The social robot used for our experimentation is the NAO robot model developed by SoftBank Robotics. Such robotic platform is natively equipped with a set of internal sensors (such as camera, microphones, and proximity sensors), and actuators (e.g., head, Rarm, and Larm), and it provides a set of essential behaviours (e.g., motion, people tracker). Figure 2 shows the architectural schema of the designed social robot for providing suggestions by human–robot interactions and environmental sensing. Dashed rectangles indicate behaviour modules provided natively by the NAO robotic platform. In the following, the relevant elements of the architecture are detailed.

Knowledge base The final purpose of the social robot is to improve human well-being by providing suggestions based

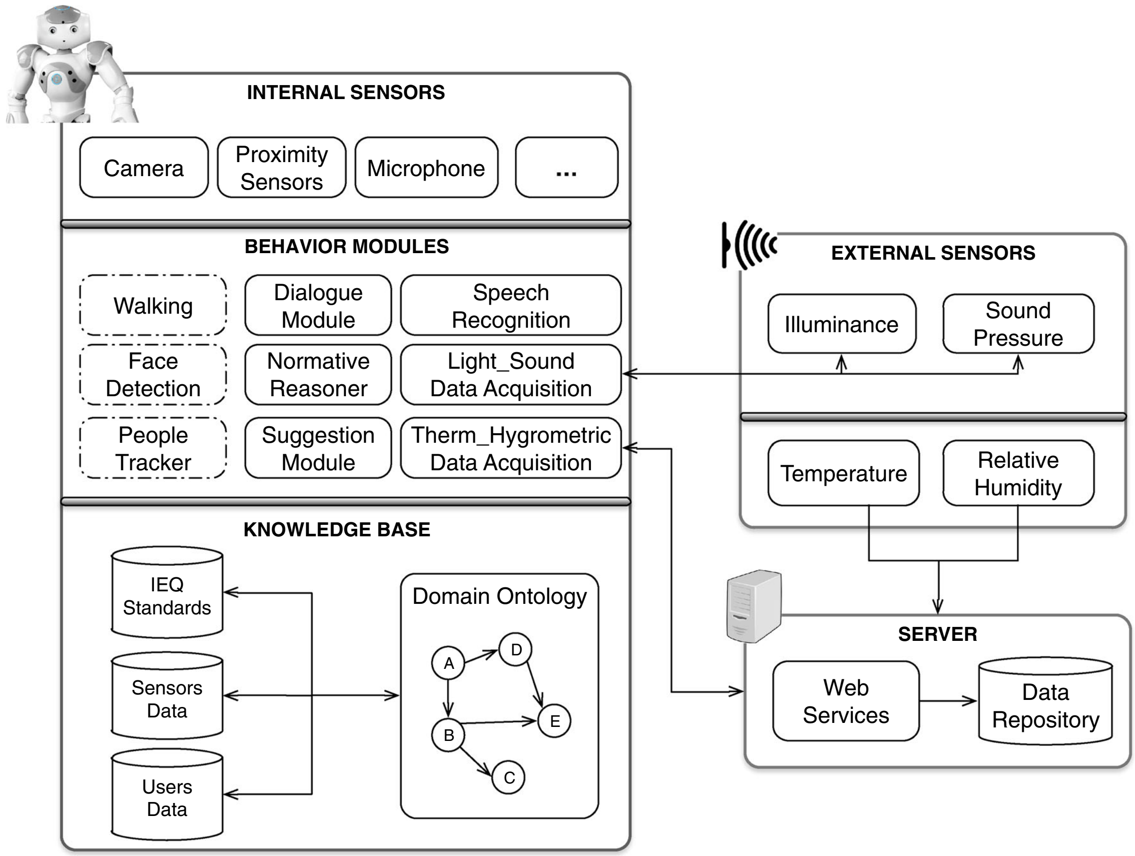

Fig. 2 The architectural schema of the proposed social robot for monitoring environmental quality

on (i) the current information that was perceived from the environment; (ii) user preferences and perceptions acquired through social interactions and (iii) static knowledge about the IEQ standards for occupant wellness in indoor environments. The *Knowledge Base* is the central store containing all the necessary robot's knowledge. It contains the current instance of the previously defined domain ontology, related to the current session of the monitoring campaign, that stores knowledge currently being used. The robot dynamically populates such instance by collecting sensors measurements and user's answers to the POE survey. As previously said, we choose the first-order logic as a formalism to represent the robot's ontological knowledge. In doing so, we also developed a module that translates an instance of the ontology into a first-order logic formalism. It expresses ontological concepts and relations in terms of logical sentences about objects of the domain of interest with predicate and function symbols. Figure 3 shows a portion of an IEQ ontology instance and the resulting first-order logic representation. Moreover, the Knowledge Base contains also dedicated SQL databases that store all static information and dynamic knowledge acquired during the monitoring campaign. Each result of a monitoring session is opportunely saved for making historical reports.

```
...
<Employee rdf:about="http://www.owl-ontologies.com/
EnvOntology.owl#Mario">
  <Gender>
    <Gender rdf:about="http://www.owl-ontologies.com/
EnvOntology.owl#male"/>
  </Gender>
  <works>
    <Job_Area rdf:about="http://www.owl-ontologies.com/
EnvOntology.owl#office">
      <Temperature>
        <Temperature rdf:about="http://www.owl-ontologies.com/
EnvOntology.owl#24"/>
      </Temperature>
      <SoundLevel>
        <SoundLevel rdf:about="http://www.owl-ontologies.com/
EnvOntology.owl#60"/>
      </SoundLevel>
      <Plane_Illuminance>
        <Plane_Illuminance rdf:about="http://www.owl-ontologies.com/
EnvOntology.owl#450"/>
      </Plane_Illuminance>
    </Job_Area>
    ...
  </works> ...
```

```
world ([...
    type(office,job_area), temperature(office,24), soundlevel(office,60),
    plane_illuminance(office,450), gender(mario,male), works(mario,office),
    ...])
```

Fig. 3 A portion of IEQ ontology instance and the resulting first-order logic representation

Table 11 Thermal and visual sensation values

Thermal Sensation	Visual sensation	Value
Cold	–	− 3
Cool	–	− 2
Slightly cool	Too dark	− 1
Good	It is ok	0
Slightly warm	Too bright	+ 1
Warm	–	+ 2
Hot	–	+ 3

Dialogue module and speech recognition Two modules have been developed for allowing the social robot NAO to interact with a user to capture his/her preferences and perceptions about the environment (s)he lives. As aforementioned, a well-known method in the field of the Indoor Environmental Quality evaluation for collecting such data is the POE questionnaire. As we have seen, the satisfaction with the indoor environmental quality is evaluated by several criteria, including heat, lighting and noise. A survey was designed to obtain user opinions about subjective thermal, visual and acoustic satisfaction as well as user preferences. Such a questionnaire includes among others, questions about: thermal sensation regarding the indoor thermal ambient based on the ASHRAE seven-point sensation scale [28] ranging from very satisfied (+ 3) to very dissatisfied (− 3) (see Table 11); visual sensations such as illuminance level conditions (see Table 11); and acoustic sensations such as noisy ambient perception. Hence, the *Dialogue Module* allows the robot to engage a dialogue with the user, to perform the post-occupancy questionnaire and simultaneously acquiring the user answers. Such modules rely on the *Speech Recognition* module, which uses the Google speech recognition technology. It sends the recorded audio and receives a text transcription from the Speech-to-Text API service.

Light_Sound and Therm_Hygrometric Data Acquisition Modules The NAO robot is not natively endowed of internal environmental sensors. Thus the current implementation of the system has been realized by using external devices that Nao embeds into an adequately built backpack during the monitoring campaign (Fig. 4).

Notably, we use three kinds of external devices (see photo in Fig. 5) for acquiring four environmental parameters (i.e., temperature, relative humidity, sound pressure and illuminance levels): (1) the SHT31 Smart Gadget endowed with humidity and temperature sensors, data logging capabilities and Bluetooth Low Energy (BLE) connectivity; (2) the ISO-Tech ILM350 Digital Lux Meter designed to give light level readings up to 50,000 lux. It has a wired remote sensor that allows light measurements away from the subject area to be collected. Thus, it minimises shadowing errors; (3) finally we use the microphone of a Huawei Smart-phone for acquiring sound pressure levels.[2] Due to the availability of Bluetooth connection, the data collected by the Hygro_thermal sensor are directly sent to a server, where are also deployed the web services that pre-process such data, in particular providing their mean value and the standard deviation. The *Therm_Hygrometric Data Acquisition* module invokes such web services to obtain the right mean value and standard deviation of the temperature and the humidity values acquired during the temporal window of a single session of the monitoring campaign. Conversely, the data related to the illuminance and the sound pressure levels are communicated by the user to the robot. The *Light_Sound Data Acquisition* module acquires the user answers. All these data are sent to the normative reasoner.

Normative reasoner module The *Normative Reasoner* implements the algorithm for evaluating the compliance to the

Fig. 4 Nao with its backpack containing the external sensors

Fig. 5 Kit of devices used by Nao

[2] It is worth noting that we did not use the Nao's internal microphone because it does not give correct measurements, which are influenced by the noise produced by its cooling fan that is positioned near the microphone.

normative standards for the Indoor comfort introduced in Sect. 5. It has been implemented in Bordini and Hübner [8], that is a Java-based interpreter of an extended version of the AgentSpeak Language [23]. AgentSpeak(L) is an extension of logic programming to provide an abstract framework for programming according to the BDI (Beliefs–Desires–Intentions) paradigm. A Jason code listing usually contains a specification of a set of beliefs and a set of plans. In particular, such framework allows representing the belief base (*bb*) as a fragment of first-order logic using a logic programming syntax as follows.

$$bb ::= at_1 \cdot at_2 \cdot \quad \ldots \quad at_n$$
$$at ::= P(t_1, \ldots, t_n)$$

The atomic formulae *at* of the language are predicates where P is a predicate symbol, and $t_1, \ldots, t_n$ are standard terms of first-order logic.

A Jason plan is composed of three main elements organized in the following form:

$$plan ::= head < body$$
$$head ::= triggeringEvent : context$$

A plan is formed by a triggering event, followed by a conjunction of beliefs representing a context. The body of the plan is a sequence of actions or (sub)goals to achieve. Such actions are also defined as first-order predicates.

For the scope of this work, the Belief Base holds all the information the robot needs for accomplishing a single session of the monitoring campaign.

In the following, a Jason implementation of the Algorithm 1 is shown. In particular, the code in Listing 1 implements the preparatory stage for the Algorithm 1. It shows the Jason code that allows for loading data from the Knowledge Base (see STEP 1) related to the current monitoring session, such as the set of recommendations (here generically named norms) and the state of the world that are the inputs for Algorithm 1. Then, STEP 2 invokes the plan for evaluating the compliance with the standards based on the current state of the world and the set of recommendations.

```
+! loadDataFor(Employee) : true <-

        /*** STEP 1 ***/
        utility.getNormList(NormList);
        utility.loadWorld(Employee,World);

        /*** STEP 2 ***/
        !evaluate_complaince_for(Employee,World, NormList);

        /*** STEP 3 ***/
        !clearBelif_Base(Employee);
```

Listing 1 Jason code example for loading data from KB.

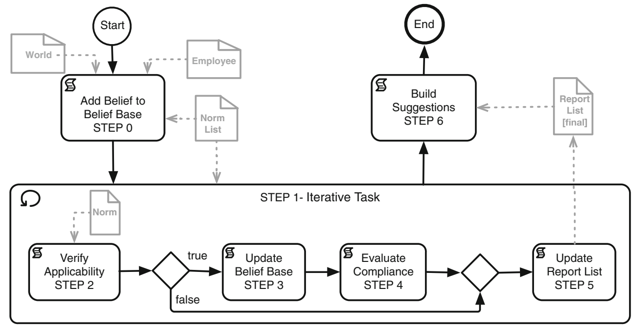

Fig. 6 Work-flow representation of Algorithm 1

Listing 2 is the Jason implementation of Algorithm 1 and Fig. 6 shows its graphical representation through a work-flow. The inputs elements are the employee name, the norm list and the current state of the world. At first (STEP 0), some beliefs are added to the belief base. The first one will contain the list of standards applicable to the current situation described in the current state of the world, and the second one will contain the report of the compliance evaluation. All the norms are also added to the current belief base.

Thus, for each norm, the applicability condition is tested over the current state of the world (STEP 2). If it is verified, the belief base will be updated (STEP 3), then according to the current deontic operator, the state of the affair will be tested over the state of the world (STEP 4). Three kinds of results are possible:

– *Result A* the norm *IDnorm* is applicable, but the state of the world is not compliant with such norm;
– *Result B* the norm *IDnorm* is applicable, and the state of the world is compliant with such norm;
– *Result C* the norm *IDnorm* is not applicable.

The report list is iteratively updated with last results (STEP 5). Finally, STEP 6 invokes the plan for building suggestions according to the final report list.

```
+! evaluate_compliance_for(Employee,World,NormList) : true
    <-
    /*** STEP 0 ***/
    /* add beliefs to Belief Base */
    +applicableNormList(Employee,[]);
    +reportList(Employee,World,[]);
    .length(NormList,LenN);
    for (.range(I,0,LenN-1)){
        .nth (I,NormList,IthNorm) ;
        +IthNorm;
    }
    /*** STEP 1 ***/
    /* Iterative task */
    for(norm(role(R),goal(G),state_affair(Rho) condition(
     Phi), deont_OP(Type))          [norm_id(ID_Norm)]){

          /*** STEP 2 ***/
            /* Verify norm applicability */
```

```
          CurrentNorm=norm(role(R),goal(G),
    state_affair(Rho),condition(Phi),        deont_OP(Type),
     [norm_id(ID_Norm)];

          !test_condition(condition(Phi),        World,Is
    _Applicable);

          if(Is_Applicable=true){
              /*** STEP 3 ***/
              /* update the Belief Base */
              ?applicableNormList(Employee,List);
              -+applicableNormList(Employee,        [
    CurrentNorm|List]);

        /*** STEP 4 ***/
        /* Evaluate Compliance */
              if(Type=discouraged){
                  D_rho=neg(Rho);
              }
              if(Type=recommended){
                  D_rho=Rho;
              }
              Condition_to_Test=condition(D_rho);
              !test_condition(Condition_to_Test,
    World,Is_Compliant);

              if(Is_Compliant=false){
                 ID_Result_Code=2;    /*Result A */}
              else{ID_Result_Code=1;/*Result B */}
          }
          else{ID_Result_Code=3; /*Result C */}

       /*** STEP 5 ***/
       /* update Report List */
       ?reportList(Employee,World,ListResult)
       Head=[ID_Result_Code,ID_Norm];
       ListResultNew=[Head|ListResult];
       -+reportList(Employee,World,
    ListResultNew)
    }
    /*** STEP 6 ***/
    ?reportList(Employee,World,LIST);
    !build_Suggestions(Employee,World,LIST).
```

Listing 2 Jason Implementation of Algorithm 1

Suggestion module The *Suggestion Module* allows the robot to give the appropriate suggestions according to the compliance results and the user preferences and perceptions. In particular, for each kind of comfort (i.e., thermal, acoustic and visual), four different situations are considered (see Fig. 7) based on the user satisfaction related to the current quality of the environment and its compliance with the comfort standards.

The green square (bottom left) of Fig. 7 represents the better situation in which the indoor environmental quality lies within the value established by the recommendations, and the user is satisfied by his/her environmental conditions. The robot has no practical suggestions. The red square (top right) represents the worst situation. In this case, the environmental condition does not respect the quality standards, and the user is experiencing a discomfort situation. In such cases, the robot gives operative suggestions for changing the environmental conditions and for leading them within the range of the recommended values of the standards. The most exciting situations are represented by the yellow (bottom right) and orange (top left) squares, highlighting that the conformity to the standard does not always imply the user wellness and vice versa. In such particular cases, the robot gives operative suggestions taking into account the user preferences and trying, when it is possible, to maintain or lead the environment into the compliance zone.

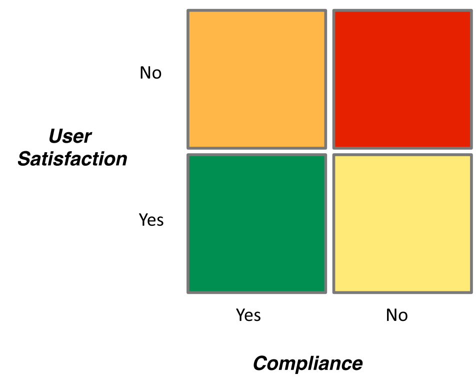

Fig. 7 General representation of the four main situations: (i) user satisfied and environment not compliant with standards (yellow); (ii) user not satisfied and environment not compliant with standard (red); (iii) user not satisfied and environment respects the standards (orange); (iv) user satisfied and environment respects the standards (green). (Color figure online)

7 Pilot User Study

In the case under study, the task assigned to the robot is to evaluate the comfort conditions of individuals that work inside offices. In doing so, it has to monitor if the user working environments are compliant with the recommendations provided by the official standards. Without loss of generality, we consider only some of the recommendations taken from the standard related to the spaces used as office and user activities such as writing, reading or working with a laptop. Thus, in this case study, the robot knows the following six norms.

N_1 It is recommended that the temperature is lower than $25°C$ and greater than $20°C$ if the humidity is lower than 30% and the environment is a job area, in the winter season.

N_2 It is recommended that the temperature is lower than $23°C$ and greater than $20°C$ if the humidity is lower than 60% and greater than 30% if the environment is a job area, in the winter season.

N_3 It is recommended that the temperature is lower than $27°C$ and greater than $24°C$ and the humidity is lower than 30% if the environment is a job area, in the summer season.

N_4 It is recommended that the temperature is lower than $25°C$ and greater than $23°C$ and the humidity is lower than 60% and greater than 30% if the environment is a job area, in the summer season.

N_5 It is recommended that the illuminance on the work-plane is at least 500 lx if the environment is a job area.

N_6 It is discouraged that sound level is greater or equal than 55 dB if the environment is a job area.

It is relevant underling that we can give to the robot other recommendations (defined inside its knowledge sphere) in any time without any change in the code of the compliance reasoning. It is due to the cognitive capabilities of the robot to reason about the concept of recommendation and its knowledge about the domain in which it is operating.

The experimental tests were carried out in different offices located in the National Research Council building in Palermo. The robot interacted with ten individuals during the monitoring campaign. Each session of the monitoring campaign is planned as follows. The robot detects the occupant of the office, and it moves towards him/her. When it is close to the user, it gives him/her instructions for positioning the external devices in appropriate positions to take the right measurements. While the sensors acquire the measurements, the robot applies the POE questionnaire to the user. Finally, it analyses the results and gives the user a report about his/her environmental quality, giving some suggestions when it is the case. Each session takes about 10 minutes.

One of the advantages of this study consists of the correct positioning of the sensors because it can jeopardise the accuracy of the acquired values. Hence, the robot asks the user to place the illuminance sensor on the desk (as suggested by the standard EN12464) where, in general, it cannot be placed a permanent sensor of a traditional BACS.

In the following, it is reported the whole dialogue between the robot (R) and Marina (U), one of the authors of the paper, during a monitoring session.

```
R: Hello, I'm Nao. What's your name?
U: My name is Marina.
R: Nice to meet you, Marina. I'm here for en-
   suring your well-being. I have to gather
   some environmental parameters. But I also
   need your collaboration. Take the sensor
   in my belt; place it near you. Tell me ok,
   when you finished.
U: Ok, finished.
 /** Hereafter, Nao starts the POE Survey **/
R: How old are you?
U: I'm 31 years old.
R: What is your role in the office?
U: I'm a Researcher.
R: How much time do you usually spend at work?
U: 8 hours.
R: Ok, the time you usually spend at work is 8
   hours. How do you feel right now?
   Choose among: hot, warm, slightly warm,
   no change, slightly cool, cool, cold
U: I feel good
R: How do you prefer to feel right now?
   Choose among: much warmer, warmer, a bit
   warmer, no change, a bit cooler, cooler,
   much cooler.
U: no change
R: Would you like some fresh air? Choose
   among: yes much more, yes more, yes but
   a little bit more, no it is ok, no I'd like
   a bit less air, no I'd like less fresh air,
   no I'd like much less fresh air.
U: no, it is ok
R: Would you like to have more manual control
   in the temperature?
U: yes
R: Do you like illuminance level condition?
   Choose among: no it is too dark, it is ok,
   no it is too bright
U: no, it is too dark
R: Do you like luminaries colour level?
U: No
R: Do you prefer warmer or cooler light?
U: I prefer the warmer light
R: Ok, you prefer warmer
   Do you control the shading system manually,
   during the day?
U: yes
R: Do you have some eye pathologies?
U: yes
R: I'm afraid, what kind of eye pathologies?
U: myopia
R: Usually, is your office too loud?
U: no, it isn't
R: Do you think is here stuffy? Choose among:
   yes always, yes sometimes, for me is ok
U: yes sometimes
R: Is there some disturbing air flux?
U: yes
R: Do you perceive a high humidity level?
U: No
 /** Nao finished the POE Survey; now it
     acquires from the user illuminance and
     sound level that the user reads from the
     sensor placed on his/her desk **/
R: Now, can you read the value shown by
   the illuminance sensor?
U: 510
R: Ok, Can you read the sound pressure level
   from the smartphone?
U: 50
R: Thank you for your cooperation.
   Just another request. Can you put again
   the sensor in my belt? Tell me ok,
   when you finished.
U: ok
 /** In this meanwhile, Nao has also acquired
     data coming from the Smart Gadget device
     about temperature and relative humidity,
     and it is elaborating the results. **/
```

After such interaction, the robot creates an IEQ ontology instance, which is translated in a representation of the state of the world. In the following, the most significant parts of the information are reported.

```
world([
/***data of the user**/
type(marina,employee),
gender(marina,female),
age(marina,31),
role(marina,researcher),
time_at_work(marina,8)
performs(marina,writing),
type(writing,activity),
is_afflicted(marina,miopia),
type(miopia,eye_pathology),

/***data about the environment**/
works(marina,office),
type(office,job_area),
temperature(office,25),
humidity(office,33),
plane_illuminance(office,510)
soundlevel(office,50),

/***user perceptions**/
perceives_disturbing_air_flux(marina,yes),
type(yes,air_flux_percept),
perceives_loud_environment(marina,no)
type(no,loud_percept)
perceives_high_humidity_level(marina,no)
type(no,humidity_percept)
feels(marina,good)
type(good,heat_percept)
perceives_illuminance(marina,too_dark)
type(too_dark,illuminance_percept)

/***user preferences**/
likes_control_temperature(marina,yes)
type(yes,temperature_control_preference)
likes_air_fresh(marina, it_is_ok)
type(it_is_ok,air_fresh_preference),
likes_luminary_colour(marina,warmer)
type(warmer,luminarie_colour_preference)
prefers_to_feel(marina,no_change)
type(no_change,temperature_preference)])
```

Based on such state of the world and the previous recommendations, the report list (see code shown in Listing 2) that will be used for building appropriate suggestions is the following:

1. Found out not applicable Recommendation N_1 for Marina.
2. The current situation for Marina violates the Recommendation N_2.
3. Found out not applicable Recommendation N_3 for Marina.
4. Found out not applicable Recommendation N_4 for Marina.
5. The current situation of Marina is compliant with Recommendation N_5.
6. The current situation of Marina is compliant with Recommendation N_6.

Thus, according to the answers obtained from the questionnaire and the environmental measurements, the robot detects the following situations.

– The environment does not conform to the Standard of Thermal Comfort. Current temperature is greater than the max threshold recommended by the standard in the winter months. Nevertheless, the occupant feels good; she would like to have more manual control in the temperature.
– The environment conforms to the Standard of Visual Comfort, but the occupant does not like the illuminance, and she prefers a warmer colour temperature.
– Finally, the environment conforms to the Standard of Acoustic Comfort. The occupant perceives a silent environment.

Hence, Nao builds appropriate suggestions. In the following, the rest of the dialogue with Marina.

```
R: Ok Marina, now I will describe you the
   situation of thermal, visual and acoustic
   comfort with respect to your working
   conditions. I will try to give you some
   suggestions for improving your well-being
   if it is the case.
U: ok
R: Marina, the current temperature near you
   is 25 degree. You feel good in your
   environment even if it is not compliant
   with the thermal comfort standard: It is
   recommended that the temperature is
   lower than 23 degrees and greater than
   20 degrees if the humidity is lower than
   60% and greater than 30% and the
   location is a job area, in winter season.
   I suggest you to decrease the temperature
   at least to the max value of the standard
   and to verify if you are too lightly
   dressed. A lower temperature could improve
   the comfort for your work.
   Tell me next for going on or repeat
   for saying again.
U: Ok, next
R: Marina, your current plane illuminance
   is 510 lx. You perceive a bad illuminance
   although your current environment
   respects the visual comfort standard: It
   is recommended that the plane illuminance
   is at least 500 lx. Because you prefer a
   warmer color temperature, I suggest you
   to add a table lamp with warm lights
   and to verify if it is a more pleasant
   situation for your eyes.
   Tell me next for going on or repeat
   or saying again.
U: Ok, next
```

Fig. 8 Some steps of the real interaction the robot engaged with an individual

```
R: Finally, Marina your current environment
   respects the acoustic comfort standard.
   I hope to be useful to you.
   Thank you, bye-bye.
U: Bye.
```

Figure 8 shows only some significant steps of the real interaction that our robot engaged with Marina.

In the following section, the results of the monitoring campaign conducted over ten individuals will be discussed.

7.1 Results and Discussions

The experiment has been conducted in the same building, but the participants work in different rooms located on different floors. In particular, one office is situated on the underground level, while the others on the ground floor and the second floor. Only two participants share the same office, but their desks are located in very different positions. One desk is near the air conditioner and the door. Conversely, the second occupant desk is placed on the opposite side of the room in front of the wall. In each office, it is possible to regulate the temperature and lighting autonomously. Moreover, the offices have different orientations. Some are exposed to the south-east and others to the north. Thus, the illuminance level is different during the same hours of the day. Some offices have more windows than others. The windows are positioned on the wall at different height according to the office floor level. In particular, an office located on underground level does not have enough natural light because its windows look out on a lightwell.

Moreover, the environmental conditions of the experiment are not programmed a priori. They are the real ones of the working environment of the user currently interviewed. Besides, the users do not know the questions of the survey. Only one participant (i.e., Marina whose interaction with the robot was shown in the case study) had a priori knowledge of the survey.

Before starting the interview, the users are asked if they agree to store personal information. In a positive case, personal information like name, age, and user preferences are stored in a restricted-use database with no public access. Otherwise, all personal data are destroyed at the end of the interview. We maintain only the environmental measures and the final report in an anonymous record to be used in an aggregate form later.

In this experiment, ten native Italian speakers were interviewed (5 Males and 5 Females) with age ranging from 31 to 57. The language adopted for all the interviews (excerpt one

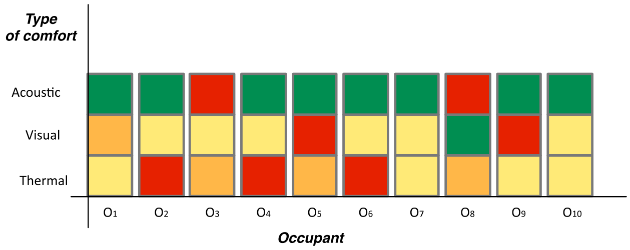

Fig. 9 Occupant's perception about thermal, visual and acoustic comfort

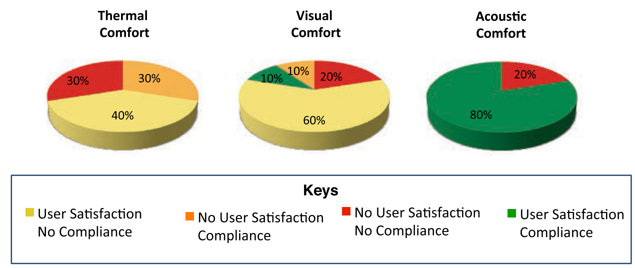

Fig. 10 Percentage values about Thermal, Visual and Acoustic comfort situations

reported in the previous section) was the Italian language. Although the limited number of tests, the results cover very different situations summarized as follows (see Fig. 9):

1. The first situation represents a result in which a user feels good, but the values suggested by the standard are not achieved (yellow square);
2. The second one represents a result in which user does not feel good, and the values suggested by the standard are not achieved (red square);
3. The third one represents a result in which a user does not feel good, but the values suggested by the standard are achieved (orange square);
4. The last situation represents a result in which a user feels good, and the values suggested by the standard are achieved (green square).

In particular, the results of the experiment showed that some individuals often do not realize discomfort situations. They have been adapting to uncomfortable conditions. Thus, they feel good also in environments whose conditions are very far from the range of the recommended values. As an example, during an interview session, an individual perceived good illuminance while his/her plane illuminance detected by the sensor was 175 lx. The minimum value recommended by the standard is 500 lx. (S)he did not seem aware that the room was too dark. (S)he realized such a situation only after interacting with the robot, which suggested to increase the brightness of the working plane and to check if it improves her/his visual comfort.

Vice versa, some occupants did not feel good in environments that were compliant with the standards. Some of them, for example, felt cold although the thermal comfort parameters were respected. In the cases in which the current temperature was within the recommended range but lower than the maximum threshold, the robot suggested to increase the temperature to the maximum recommended level and to verify the adequacy of the dressing to the season. Other people instead chose knowledgeably to stay in a determined situation, although it did not follow the standard recommendations.

The bar chart in Fig. 9 summarizes the overall results of comfort situations detected for each interviewed worker (i.e., the occupant of the office).

As we can see, acoustic comfort is generally conformed to the standard. The only situations in which has been experienced acoustic discomfort is related to individuals that share the same office. Thus, the general surrounding chat of other people naturally leads to a higher level of noise. The most critical situation is instead detected about thermal and visual comfort. Only in four situations, the standards are respected, but the occupants do not feel good. In all other cases, the standards values of comfort are not respected. It is worth to underline that in many of these, the occupants feel good although the environments are not compliant with the standards. The only situation of visual comfort that is compliant to the standard is detected in the office of Occupant O_8. However, O_8 is an expert in the field of the illuminance, and (s)he was aware of the poor illuminance condition of her/his working plane. Thus, (s)he has increased the brightness of her/his desk by using table lamps.

Figure 10 shows the aggregated results according to each kind of comfort. As we can see, in case of thermal comfort, the environment is out of the recommended value in 70% of cases. The situation is worse in the case of visual comfort, where the environment is uncompliant with the standard in 80% of cases. From another point of view, Fig. 11 shows an aggregated vision of how many times the compliance is reached and how many times the users are satisfied. We can see as, although in the 57% of cases the compliance with the standard is not reached the user is satisfied in the 63% of cases.

Moreover, during the monitoring campaign, we never obtained full environment compliance with the acoustic, visual and thermal standards. Conversely, the complete user satisfaction for all kinds of comfort is obtained in 20% of cases.

Hence, the experiment highlighted that the use of a social robot provides several advantages. First of all, it resolves the issue related to the acquisition of correct measurements in specific locations close to the user that is expensive and often infeasible with a traditional BACS. Secondly, the ability of

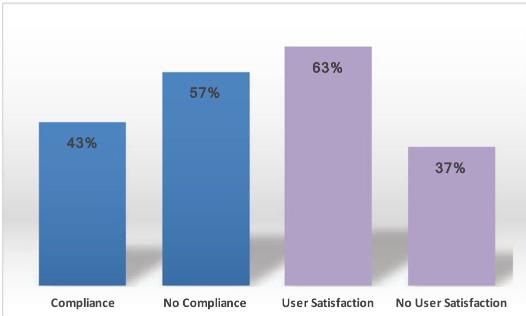

Fig. 11 Percentage values of environmental compliance with the standards and percentage values of whole user satisfaction

a social robot to gather also information by the user about his/her perceptions and preferences allows providing personalised suggestions to improve his/her well-being. Moreover, it often occurs that some kinds of tasks (especially the mental ones) absorb all our attention, making us imperceptible about our surroundings. The use of social robots results most useful for making the user sensible of his/her real situation and supporting him/her to reaching more comfortable working conditions.

On the other hand, two main working hypotheses define the drawback of the proposed approach. Firstly, the environment is conceived to be robot-friendly, meaning that the robot can move throughout the space without relevant obstacles as steps, cables, or other. Secondly, the user should be basically experienced to interact with a robot in terms of correct pronunciation and cooperation. Indeed, using only speech interaction may cause some problems of misunderstanding. In order to mitigate them, during the interaction, if the user does not understand something, the Nao may repeat the sentence, or if the user needs an explanation about concepts such as the colour temperature, the robot sends her/him an email with the definition of the concept also using figures, if it is the case.

8 Conclusions

We gave a contribution to assisting humans in many activities for improving their quality of life by using a social robot, in particular for increasing their well-being about indoor environmental quality. We developed a social robot with the ability for acquiring not only data about the state of the physical environment employing external sensors, but also useful information about psychological and physiological states of the user by performing a post-occupancy evaluation questionnaire. The primary issue has been related to endow the robot with the cognitive capability for reasoning about normative standards. In doing so, we have developed an approach based on (i) a semantic representation of data through an ontology that formalizes the indoor environment quality domain; (ii) a formalization of normative standards based on deontic logic; and (iii) the definition of an algorithm for reasoning about the compliance of the environment with respect to the normative standards.

Ten individuals participated in the experiment. The robot interacting with an individual acquires data about the environmental conditions and user preferences and perceptions simultaneously, that will be used for giving personalised suggestions for solving possible discomfort situations.

The results show very different scenarios. The better is when the user feels good, and the values suggested by the standard are achieved. In this case, the robot has no useful suggestions. The worst scenario is when the user does not feel good, and the values suggested by the standard are not achieved. In such cases, the robot gives operative suggestions for changing the environmental conditions and for leading them within the range of the recommended values of the standards. The most interesting scenarios are when the user feels good, but the values suggested by the standard are not achieved, and when the user does not feel good, but the values indicated by the standards are achieved. These situations highlight that compliance with the standards does not always imply user wellness and vice versa. In such particular cases, the robot gives operative suggestions taking into account the user preferences and trying, when it is possible, to maintain or lead the environment into the compliance zone. The experiment has also demonstrated that the use of a social robot reveals useful for making the user aware of his/her situation and for leading him/her to a more comfortable working condition.

Finally, the proposed robot-based approach for monitoring indoor environmental quality mitigates some the limitations of traditional methods, such as (i) the complex integration process of sensors especially in existing older buildings; (ii) the loss of performance due to the acquisition of measurements in wrong locations and above all (iii) the stress of automation that the user feels when the automatic adjustments performed by a traditional automation control system are not in line with his/her current needs or when the reasons for such corrections are not clear for the individual.

Future work Based on the positive feedback by the users generally satisfied to interact with a robot, further studies are planned for the future. In particular, for increasing the acceptability of the system, we are developing a new robot behaviour allowing to autonomously collect the environmental parameters by a new set of sensors to take measurements directly without distracting the user. In addition, a face recognition tool could be added to identify the user. However, this aspect entails further privacy issues that require a preliminary users' consensus. Besides, for improving the physical architecture of the whole system, we are currently working to develop a low-cost embedded system endowed with several kinds of environmental sensors. In particular, we are considering sensors for monitoring also the quality of the air. Thus, new monitoring campaigns can be extended in the future for also evaluating the Hygienic comfort of the working environments. Other studies will also include the development of new robot's capabilities for suggesting optimized layout configurations, for expanding the data acquisition to more data types and for testing the approach in more indoor environments. Finally, we are also considering probabilistic models suitable to face the problem of the uncertainty for studying the loss of comfort during the day.

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Compliance with Ethical Standard

Conflict of interest The authors declare that they have no conflict of interest.

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