Integration of Human Comfort Indicators in a Holistic Framework of Next-Generation Energy Performance Certificates

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Abstract. The building sector constitutes the major energy-intensive domain, with 40% of Europe's final energy demand. Despite the increased energy consumption in buildings, there is no sufficient information about the quality of indoor environmental conditions they offer to the occupants. Indoor environmental conditions play a major role in the quality of life, yet the quality assessment is not well-known to the general public. Recent developments in the Internet of Things (IoT) domain can help in the evaluation of indoor conditions and lead the building sector into the Industry 4.0 era. Moreover, the introduction of new key performance indicators can raise the awareness of relevant stakeholders and lead to more energy-efficient homes providing enhanced human comfort conditions. This study aimed to identify human comfort and well-being key performance indicators which could be included in the next-generation energy performance certificates and extract insights on the occupants' comfort in the two pilot buildings with the minimum available information via a non-intrusive (to the occupants) procedure. The proposed set of human comfort and well-being indicators deals with the aspects of thermal comfort, visual comfort and indoor air quality. Only quantitative key performance indicators were considered within the study, as their calculation is based on acquired data from the pilots' IoT infrastructure.

Keywords. EPC, human comfort, KPIs, IAQ, thermal comfort, CO2, D^2EPC

1. Introduction

Energy Performance Certificates (EPCs) are among the most essential information sources regarding the energy performance of building stock. EPCs provide transparent information for building owners and real estate stakeholders. However, when the EPCs schemes were developed, the new technologies, which are present nowadays, did not exist.

Despite the increased energy consumption in buildings, there is no reassurance about the quality of indoor environmental conditions they offer to the occupants. Indoor environmental conditions play a major role in the quality of life, yet the assessment of the quality is a concept not well-known to the general public. Recent developments in the internet of things (IoT) domain enable the acquisition of a multitude of ambient condition metrics that enhance the assessment of indoor conditions.. Moreover, the introduction of new key performance indicators (KPIs) can raise the awareness of relevant stakeholders and lead to more energy efficient homes taking into account the human comfort and wellbeing.

This study presents the approach followed in the H2020 D^2EPC project for monitoring and assessing indoor environmental conditions in a building. Only quantitative KPIs are considered within the D^2EPC human comfort and well-being indicators, as their calculation is based on acquired data from the pilots' IoT infrastructure.

1.1 Next-generation EPCs

The study, performed under the H2020 project "Next-generation Dynamic Digital EPCs for Enhanced Quality and User Awareness (D^2EPC)" (Seduikyte et al., 2022) demonstrated the current EPC schemes' quality and weaknesses and presented the dynamic

EPC's novelty aspects. The novel aspects include the following indicators:

- the smart-readiness level of the buildings (SRI)
- human comfort and well-being (HC&W) indicators
- sustainability-related indicators (life cycle assessment (LCA))

Also, the mentioned study analysed the introduction of building information model (BIM), digital twin, geographic information system (GIS) and financial schemes for the next-generation EPCs.

Another study (Koltsios et al., 2022) in the framework of D^2EPC project presented a detailed technological concept for a novel dynamic EPC framework which should be based on (near) real-time field data.

1.2 Human comfort and well-being key performance indicators

A key performance indicator (KPI) is a performance measurement which is calculated upon elements extracted from the system (M. Deru, P. Torcellini, 2005). It is utilised to evaluate the system's success either by a systematic improvement of its value or its preservation above-desired limits. KPIs can be both qualitative and quantitative.

To perform the KPI calculation, specific information from all relevant sources is needed. A metric needs to be directly measurable (or indirectly determined) and clearly defined in terms of units and range. The performance metrics are built upon raw data derived from measurements of a system's actual operation or measurements of a system's simulated operation based on modelling approaches.

HC&W indicators proposed in the D^2EPC project are based on three significant domains of the Indoor Environmental Quality (DIN EN 15251):

- Indoor Air Quality (IAQ) examines the parameters that affect the human respiratory system function as well as the building's ability to refresh the inhaled air. Poor indoor air quality affects occupants' health, productivity, and comfort. IAQ matters extremely since we spend most of our time indoors.

- Thermal comfort, which is defined as the level of human satisfaction with the existing thermal conditions inside a space. A properly heated and cooled space further contributes to human well-being, especially in places with extreme weather conditions.

- Visual comfort, which is expressed as the level of human satisfaction with the visual environment. A balanced light provision maximises the occupant's performance and eliminates eye tiredness and potential damage to the eye lenses. Combined with daylight-based illumination and access to the views of the outdoors, the optimal visual environment is achieved.

Thermal Comfort affects the energy consumption as it dictates the preferred (or recommended) indoor temperature conditions which are directly related with the consumption of HVAC devices. Visual Comfort is essentially connected with the lux levels in the indoor space and as a result it affects the lighting equipment consumption. Lastly, bad indoor air quality conditions might point to an installation of a ventilation system which influences the energy consumption as well. Acoustic comfort is a very significant pillar of the indoor environmental quality. However, within D^2EPC it is considered that Acoustic comfort is the least correlated IEQ factor with the energy consumption, thus it was excluded from the HC&W framework.

This study aimed to identify human comfort and well-being KPIs which could be included in the next-generation energy performance certificates and extract insights on the occupants' comfort in the two pilot buildings with minimum available information via a non-intrusive (to the occupants) procedure.

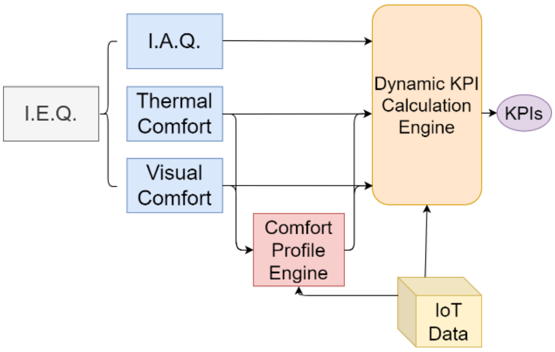
2. Methodology

2.1 Introduction

The HC&W indicators are part of the dynamic indicators to be delivered within D^2EPC project. They are based on actual IoT measurements as well as limits and boundaries (of the corresponding indoor ambient conditions metrics) recommended by European and National standards and frameworks. More specifically, the extracted time-series data are compared to the proposed boundaries/limits and further aggregated on specific time intervals (e.g. yearly) in order to yield indicative values that will be monitored under the context of the building's comfort assessment. Beyond the predefined limits, a comfort profiling engine is also utilised to deliver a personalised comfort assessment based on the occupant's preferable conditions. Its purpose is to analyse through data-driven methods the collected data from the pilot infrastructure and identify the occupant's comfort boundaries implying that the optimal visual/thermal conditions for the occupant are dictated by her/himself. Figure 1 provides a conceptual representation of the overall methodology.

Figure 1

Methodology of the HC&W performance framework



The whole methodology has been envisioned to provide insights on the occupant's comfort and well-being with already available or easily-accessible information in accordance with what is dictated in the relevant bibliography. Towards this direction, the analysis performed within D^2EPC was segmented into three stages. The first one concerned the literature research on scientific publications, standards and guidelines for the thermal/visual comfort and indoor air quality. The second one included the identification of available information (i.e., environmental metrics) from the previously installed IoT devices in the project's demonstration cases. Finally, the last stage incorporated a techno-economical feasibility analysis to shed light on the IoT equipment that would supplement the pilot IoT infrastructure with well-established and non-intrusive devices.

2.1 Definition of HC&W Performance Indicators

The outcome of the analysis highlighted the environmental metrics to be monitored in occupied spaces within the D^2EPC HC&W Framework. In the Thermal and Visual Comfort case, the indoor dry-bulb (air) temperature, relative humidity and indoor illuminance have been selected. Regarding IAQ, the indoor CO_2, VOCs and PM2.5 concentrations have been comprised in the framework as main IAQ indicators. Other IAQ metrics such as PM_{10}, Benzene, Formaldehyde, Radon concentrations and the ventilation rate have also been examined and included as complementary indicators, provided that they will not be monitored in the project's pilots.

The KPIs selected for the HC&W framework are presented in Figure 2.

To translate the IoT series data into actual indicators and infer the comfort performance, three long-term evaluation methodologies have been obtained by the literature.

Figure 2

Human comfort and well-being indicators

Thermal Comfort Indicators	Deviation from the temperature range	
	Thermal degree hours	
	Deviation from the humidity range	
	Deviation from the acceptable Wet-Bulb Globe Temperature levels	
	Humidex levels	
Visual Comfort Indicators	Deviation from the set Illuminance boundary	
	Deviation from the standard Illuminance levels	
	Set visual degree hours	
	Standard visual degree hours	
Indoor Air Quality Indicators	Main	Footprint of Indoor CO2
		Footprint of Volatile Organic Compounds (TVOCs)
		Footprint of Particulate matter <2,5 μm (PM 2.5)
	Complementary	Ventilation rate (air flow)
		Footprint of Benzene
		Footprint of Formaldehyde
		Footprint of Radon
		Footprint of Particulate matter <10 μm (PM 10)

The "Deviation from the defined range" (Level(S) 4.2) calculates the % of hours during which the indoor conditions were out of defined boundaries. For a period of interest, the total number of hours when the space is occupied (i.e., between the timestamps t_0 and t_1) is given by counting the remaining timestamps after filtering out the ones that correspond to zero occupancy:

$$\sum_{i=t_0}^{t_n} 1 \ (if\ occupancy\ \neq 0) \tag{1}$$

where,

t_0: initial timestamp

t_1: final timestamp

the hours out of range are calculated by counting the timestamps during which the measurement X was outside the predefined boundary $[X_{up}, X_{bot}]$:

$$\sum_{i=t_0}^{t_n} 1\,,\ [if\ X_{up} - \bar{X}_i < 0\ or\ \bar{X}_i - X_{bot} < 0] \qquad (2)$$

where,

X_{up} is the upper limit of the boundary

X_{bot} is Bottom limit of the boundary

$\bar{X}_i$ is the hourly averaged measurement

the deviation (%) is finally given by the division of the two quantities multiplied by 100.

"Degree Hours" (BS EN 16798-1:2019) introduce tailored weights to the frequency of deviation :

$$\sum_{i=t_0}^{t_n} w_i\,,\ [if\ X_{up} - \bar{X}_i < 0\ or\ \bar{X}_i - X_{bot} < 0] \qquad (3)$$

where w_i is defined by:

$$w_i = |\bar{X}_i - X_{up}|\ or\ |\bar{X}_i - X_{bot}| \qquad (4)$$

Lastly, in cases when the indicators are formed on grading categories, each hourly measurement is allocated to the corresponging category.

$$j^{th}\ category\!: \sum_{i=t_0}^{t_n} 1\,,\ [If\ X_{j\_bot} < \bar{X}_i \le X_{j\_up}] \qquad (5)$$

where,

X_{j_up} is the upper limit of the j^{th} category boundary

X_{j_bot} is the bottom limit of the j^{th} category boundary

The "Footprint of Indoor Environment" (BS EN 16798-1:2019) presents the quotas per category.

2.3 Research objects

Two pilots of the D^2EPC project were selected:

1st pilot. nZEB Smart House DIH, Thessaloniki, Greece (Figure 3). It is a 316 m^2 rapid prototyping demonstration infrastructure shaped as a real residential household. The house is representative of a single family, detached residential building and is already equipped with many IoT, smart home solutions that provide a lot of information about its operational characteristics.

Figure 3

nZEB Smart House DIH, Thessaloniki, Greece

2nd pilot. A mixed-use building in Nicosia, Cyprus, owned by Frederick University (Figure 4). The building is a two-storey 2000 m^2 building, built in 2007. University's cafeteria is in the ground floor, in the first floor there are three seminar halls of 220 students capacity and offices are found in the second floor. The building already has a BMS system installed to monitor and control the building's HVAC systems, lighting and appliances.

Figure 4

Mixed-use University building, Nicosia, Cyprus

2.4 Equipment

In the nZEB pilot, a multitude of IoT devices has been deployed to measure indoor ambient conditions in two distinct spaces (office and living room). More specifically, two wall-mounted sensors (one measuring temperature-humidity and the other one CO_2) have been installed in both spaces at a height of ~1,20m. In addition, two illuminance sensors have been placed on the ceilings at a height of ~2,5m. The respective metrics offered correspond to Air Temperature, Relative Humidity, Indoor Illuminance and CO_2 concentrations. The measuring interval of the devices varies from 100 to 300 seconds which is granular enough to cover the dynamic metric requirements of D^2EPC (i.e., hourly data). In the Frederick university pilot, the sensing infrastructure provides Air Temperature, Relative Humidity and CO_2 measurements at a measuring frequency of two hours. Taking into consideration that the temporal granularity of the time series data is inadequate, linear interpolation techniques have been utilised during the analysis.

3. Results

The analysis has been based on already available information from existing IoT infrastructure. Both pilots under study are located in Mediterranean countries characterised by hot, dry summers and humid, cool winters. KPIs calculations have been realised in two separate spaces per building. In the 1st pilot, a living room and an office were examined. In the 2nd pilot, data from a floor comprising offices and a canteen were provided. The extracted datasets correspond to a yearly period and have been aggregated (1st pilot) or interpolated (2nd pilot) in order to be transformed into hourly timestamps.

The thermal conditions of each space have been examined in accordance with the indoor temperature, humidity and their combined effect on the occupant. The calculations stepped on the temperature boundary 19,4°C – 27,7°C (ASHRAE 55:2019) and humidity boundary 30%-70% (Level(S) 4.2). A comfort profiling engine was also utilised for the definition of the personalised boundaries. The engine identifies patterns and trends in the user data. By applying state-of-the-art clustering algorithms on the user's historic data. It is deemed relevant to regularly occupied spaces by the same individuals towards rationalising a thermal comfort assessment on preceding data. For this reason, the canteen in the second pilot was considered out of context.

Regarding the combined effect of temperature and humidity, Humidex has been incorporated in the HC&W framework which corresponds to a thermophysiological parameter that describes how hot the conditions feel to the average person (ISO 7243:2017). It is mainly used for outdoor weather assessment, but within D^2EPC it was examined for indoor conditions as well. All three parameters were utilised to generate graphs i.e., scatterplots of temperature and humidity hourly timestamps with indications of comfort determined by humidex values. In Figure 5, two graphs for each space in the nZEB pilot are presented. The plotted data points are segmented into three categories. The red ones represent discomfort below the bottom limit (heating period), greens correspond to no discomfort, and finally, black points represent discomfort during the cooling period. Two patches have also been introduced to highlight the recommended indoor air temperature for the heating and cooling period.

Figure 5

Comfort graphs of nZEB's living room (a) and office (b)

(a)

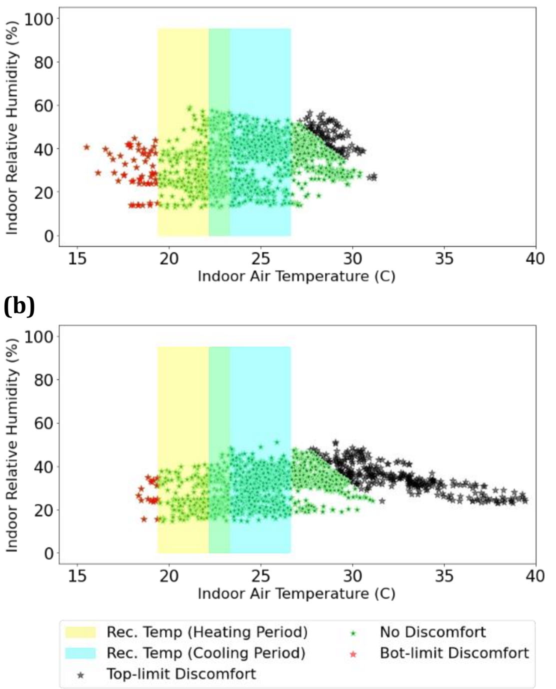


Figure 6

Comfort graphs of FRC's floor offices (a) and canteen

(a)

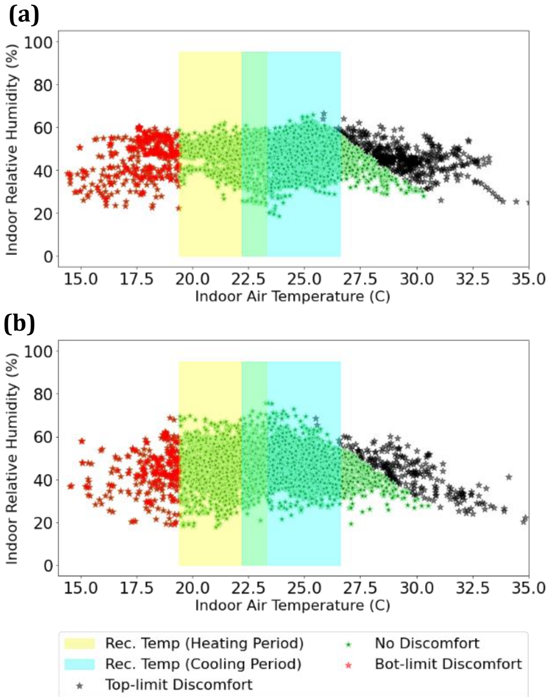


Figure indicates that the majority of hourly events are characterised as comfortable. Furthermore, there is greater tolerance in higher temperatures during the cooling period, provided that the humidity is maintained in low levels. Lastly, the extreme temperature values observed (i.e., in the office) can be explained by the lack of occupant presence since the occupancy was inferred by schedules and not acquired by actual sensor.

Similar results were extracted from the 2nd pilot in Cyprus. Figure 6 presents the offices and canteen comfort graphs in the university. The datasets are denser compared to the other pilot due to significantly less missing values. The vast majority of events are characterised as comfortable. Additionally, any extremely low or high indoor temperature value can be attributed to a lack of occupant's presence (indirect occupancy inference via schedule due to no access to occupancy sensor data).

Tables 1 and 2 present the KPIs calculation results per pilot case. Table 1 includes the indicator values in the 1st pilot. It is observed that, for the indoor temperature, 30% of the time, the conditions were not in the recommended ranges for the office and 19% for the living room. The personalised thermal assessment altered the results (19% and 26% respectively). Same behaviour was observed in the thermal degree hours i.e., a reduction for the office (755 to 418) and a rise for the living room (199 to 321). High deviation (~35%) from the humidity range has also been observed due to mainly low values in both spaces (Figure 5). Humidex results showed "little to no discomfort" for the 86% and 95% of the hours and "some discomfort" for 14% and 5% in the office and living room respectively. The Wet-Bulb Globe Temperature (WBGT) indicator (ISO 7243:2017) was not examined in the pilots as it concerns buildings with high metabolic rate activities and was deemed out of scope for these case studies. In the Visual Comfort case, the boundary of 200lux for "moderately_easy_visual_tasks" (EN 12464-1:2021) was used. However, a significant drop in the deviation was observed for both spaces when substituting the boundary with the personalised one. This implies that the occupants were more comfortable in a less luminant conditions than those dictated by the literature. The visual degree hours were not examined due to a high number of missing datapoints. Lastly, regarding the CO_2 concentrations, relatively high values were observed with most of the measurements residing in category III (CEN/TR 16798-1/2:2019).

In the 2nd pilot, the deviations calculated in the floor offices and canteen were lower (21% and 13% respectively). The personalised ranges in the offices did not alter the result (21-22%), though the degree hours have significantly increased, implying that the space has large variations in the temperature when compared to the more confined personalised boundary. The humidity deviation was within recommended limits for 98 and 96% of the time in the two spaces. In regards to Humidex, the 89% of occupied hours in the floor offices were characterised as "Little to no discomfort" and "some discomfort" for the remaining 11%. For the canteen the results were slightly better (95% and 5%). Finally, the CO_2 measurements were pretty satisfying as the concentrations in both spaces almost did not exceed the Category II limit (CEN/TR 16798-1/2:2019).

Table 1

Thermal Comfort Indicators results for the office and living room spaces in the 1st pilot

IEQ Domain	Indicator		Office	Living Room
Thermal Comfort	Deviation: temperature range		30%	19%
	Deviation: personalised temperature range		19%	26%
	Deviation: humidity range		36%	35%
	Thermal degree hours		755	199
	Thermal degree hours (Personalised)		418	321
	Humidex levels	I	86%	95%
		II	14%	5%
		III	0%	0%
		IV	0%	0%
Visual Comfort	Deviation luminance boundary		70%	81%
	Deviation luminance levels		19%	26%
	Set visual degree hours		N/A	N/A
	Standard visual degree hours		N/A	N/A
Indoor Air Quality	CO_2 Indoors	I	0%	0%
		II	0%	1.5%
		III	66%	67.1%
		IV	19.8%	28%

	V	13.7%	3.2%

Table 2

Human Comfort & Wellbeing Indicators results for the office and living room spaces in the 2nd pilot

IEQ Domain	Indicator		Floor	Canteen
Thermal Comfort	Deviation: temperature range		21%	13%
	Deviation: personalised temperature range		22%	N/A
	Deviation: humidity range		2%	4%
	Thermal degree hours		1325	675
	Thermal degree hours (Personalised)		3538	N/A
	Humidex levels	I	89%	95%
		II	11%	5%
		III	0%	0%
		IV	0%	0%
Indoor Air Quality	CO_2 Indoors	I	65%	86%
		II	34%	14%
		III	1%	0%
		IV	0%	0%
		V	0%	0%

4. Discussion

Contrary to other methodologies (e.g., PMV-PPD criteria, ASHRAE 55:2019), within D^2EPC great effort has been made to extract insights on the occupants' comfort with available information via a non-intrusive (to the occupants) procedure. It is quite unrealistic to expect multiple installations that could provide a more holistic assessment of the comfort in residences and working spaces.

Through this framework, it is attempted to infer the optimal thermal and visual conditions for the occupants utilising the indoor temperature, humidity and illuminance. All three measurements can be obtained via multi-sensing devices combining multiple metrics. Such solutions also contribute to the occupant's acceptance of the deployed equipment. Regarding IAQ , a multitude of air quality metrics with heavy impact on the occupant's respiratory system are mentioned in the literature (Levels(s) 4.1). However, provided that measuring the entirety of metrics is not considered always feasible, D^2EPC focuses on CO_2, VOCs and $PM_{2.5}$, which can be obtained through multi-sensing solutions as well. Finally, the usage of a comfort profiling engine helps define the occupants' preferable conditions without requiring any involvement from their side (through surveys or any type of feedback expected in other methodologies).

According to the results in Table 1 and Table 2, it is showcased that the thermal conditions do not deviate significantly from the recommended boundaries. In all four different spaces, the occupants feel comfortable for the vast majority of time. Concerning visual comfort, it is observed that the visual conditions that the occupants perceive as optimal differ significantly to those dictated in the literature. Regarding the CO_2 concentrations, the 1st pilot measurements are considered relatively high compared to the 2nd pilot. It is worth mentioning that measurements from different IoT infrastructures are not always comparable. Nevertheless, the indicator results act as a benchmark for the future comfort assessment of the building by monitoring their progress.

The most notable obstacles faced during the analysis concerned mainly the gaps in the 1st pilot datasets and the lack of metrics that would enable the calculation of all indicators of the HC&W Framework. In addition, the results are heavily affected by the absence of occupancy sensor data which would filter out the timestamps deemed out of scope from the analysis. To tackle this, the occupancy was inferred via scheduling hours which ultimately introduced noise in the data.

5. Conclusion

The new-generation EPC incorporates a set of performance indicators to evaluate the building from a smartness, comfort and sustainability point of view. The Human Comfort & Wellbeing KPI Framework delivered within D^2EPC addresses three IEQ domains. The Thermal and Visual Comfort and the Indoor Air Quality. Its purpose is to provide a building's comfort assessment by stepping on ambient conditions data extracted from IoT equipment in the two pilots. It combines insights from European and National standards and the outcome of a profiling engine to determine the recommended or personalized environmental metric boundaries for the calculation of each indicator.

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