Human-Centric indicators and user profiles for next generation EPCs v1

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DELIVERABLE D2.2

Human-Centric indicators and user profiles for next generation EPCs v1

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Executive Summary

This report presents the results of T2.2 – Human Comfort and Wellbeing (HC&W) Indicators Elicitation that delivers the methodology for the extraction of user behavioural profiles that influence the building's dynamic performance from the scope of occupant's comfort and wellbeing. To achieve this, the HC&W profiles definition depends solely on streaming and historic data collected by the finalised IoT infrastructures, deployed in the D^2EPC pilots. The document describes the key performance indicators (KPIs) that contribute to the monitoring of the building's progression, the algorithms and models utilised for the calculation of the indicators and lastly the desirable boundaries of the building operation in regards to various environmental metrics examined within D^2EPC.

Towards a successful assessment of the human comfort and wellbeing, the corresponding performance indicators are formed on well-defined and measurable environmental metrics originating from the building's raw data. The overall approach is envisioned to be purely data-driven based exclusively on timeseries elements in an attempt to eliminate intrusiveness.

The comfort and wellbeing indicators framework steps on three separate Indoor Environmental Quality domains, i.e., the Thermal comfort, the Visual comfort and Indoor Air Quality (I.A.Q.). Thermal and visual comfort correspond to the occupant's level of satisfaction with the indoor thermal and visual conditions while I.A.Q. examines the parameters that affect the human respiratory system function as well as the building's ability to refresh the inhaled air. D^2EPC's HC&W framework is aligned with European and national environmental and sustainability standards which emerged after a thorough research in the literature. Specifically, Level(s) is heavily considered, which is a European voluntary framework gradually adopted by building specialists towards measuring and reporting a building's environmental performance.

The literature findings and the envisioned data-driven approach are integrated into a hybrid methodology that delivers the complete framework. On the one hand, KPI reporting methodologies and relevant environmental variables along with their recommended operation limits are obtained from the standards/frameworks. On the other hand, if it's deemed feasible, the limits are substituted with personalised boundaries extracted from a comfort profiling engine that identifies patterns and trends in the user data. The engine comprises of state-of-the-art clustering algorithms and introduces several innovations in the D^2EPC.

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List of Acronyms and Abbreviations

Term	Description
EPC	Energy Performance Certificate
CMR	Carcinogenic, Mutagenic or toxic to Reproduction
EPA	Environmental Protection Agency
EPBD	Energy Performance of Buildings Directive
ETS	Environmental Tobacco Smoke
HC&W	Human Comfort & Wellbeing
HVAC	Heating, ventilation, and air conditioning
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
KPI	Key Performance Indicator
PCP	Personalised Comfort Profiling
PM	Particulate Matter
SAX	Symbolic Aggregate approXimation
SBS	Sick Building Syndrome
TVOC	Total Volatile Organic Compounds
WBGT	Wet-Bulb Globe Temperature
WHO	World Health Organisation

1 INTRODUCTION

1.1 Scope and objectives of the deliverable

The goal of this deliverable is to provide details on the Human Comfort & Wellbeing user profiles evaluated on the complete set of indicators that quantify the building's performance in regards to various environmental parameters.

This report initially delivers a concrete definition of the dynamic performance metrics and indicators as well as the principles of the followed methodological framework dictating the characteristics of the user comfort profiles (dynamic, data-driven, non-intrusive). Subsequently, the deliverable refers to the pillars of Indoor Environmental Quality (I.E.Q.) addressed within D^2EPC (Thermal/Visual comfort, I.A.Q.) and specifies the hybrid methodology to be followed for each environmental domain. This methodology concerns the merging of the data-driven approach for the user profile extraction and the findings of the literature research towards identifying the environmental parameters and methodologies to be integrated in the comfort and wellbeing assessment.

Furthermore, the document delivers the comprehensive list of the HC&W performance indicators including the indicator details, corresponding metrics, spatio-temporal granularities and calculation methodologies. Finally, it provides the specification of the personalised comfort profiling engine which will be utilised (where applicable) to apply machine learning clustering algorithms on pilot IoT data and extract the behavioural user profiles.

The next version of the deliverable (D2.7) expected at the end of the project (M36) will present the works conducted during the demonstration period (M19-M36) in regards to the KPIs and comfort profiling engine validation, fine-tuning and modifications, based on real pilot IoT data.

1.2 Structure of the deliverable

D2.2 – Human Comfort and Wellbeing Indicators Elicitation is structured as follows:

- **Chapter 2** provides a clear overview of the dynamic metrics, indicators and comfort profiles to be extracted, that will be further utilised to monitor the building's comfort performance.
- **Chapter 3** describes the domains of indoor environmental quality addressed within D^2EPC and provides insights on the hybrid methodology proposed within T2.2 for the comfort profile extraction based both on dynamic (pilot IoT data) and static (building code boundaries) elements.
- **Chapter 4** concerns the finalised selection of the thermal, visual and I.A.Q. indicators based on environmental parameters and reporting methodologies obtained by the literature (the complete list of KPIs is provided in the Annex of the deliverable)
- **Chapter 5** gives an overview of the personalised comfort profiling engine and its integration in the D^2EPC system architecture and, lastly, sheds light on the modern clustering algorithm integrated in the engine to extract comfort boundaries based on user previous behaviour.

1.3 Relation to Other Tasks and Deliverables

The identified interdependencies arising among T2.2 and other D^2EPC tasks are presented below:

- **T1.3** has delivered a comprehensive study on the most established energy performance frameworks and certifications that further address indoor environmental quality. This study will act as a basis for the T2.2 overall literature research.
- **T1.4** concerns the D^2EPC system architecture and sheds light on the modules that will materialise the dynamic KPI calculations.
- **T2.5** regards the common information model that dictates the information exchange among the project components. The task is considered critical for T2.2 as it will define the appropriate interfaces for the Personalised Comfort Profiling PCP and the dynamic KPI calculation engines
- **T3.1** has delivered the entire IoT framework responsible for information collection from pilot infrastructure. The dynamic metric requirements delivered by T2.2 has acted as a basis for the selection of IoT devices that will eventually capture the necessary ambient conditions, after a feasibility and cost-efficiency assessment
- **T5.1** will issue the D^2EPC manual which will include a brief description of the HC&W KPIs
- **T5.2** is responsible for identifying the existing pilot IoT infrastructure and define, based on the T2.2 and in collaboration with the works of T3.1, what is already measured and what type of IoT devices need to be further deployed in order to acquire the missing information.
- **T5.3** will implement the D^2EPC concepts and solutions in the demonstration cases. Consequently, T5.3 will validate and evaluate the comfort performance of each pilot, based on the indicators elicited by T2.2.

2 Overview of the Methodological Framework

2.1 Dynamic Metrics and Key Performance Indicators Definition

A system's reliable operation and future success is highly dependent on the evaluation of its progress towards intended results. To achieve this, a performance framework needs to be established in order to monitor specific aspects of the system's performance in regards to critical strategic goals and objectives. Such a framework is constituted on the basis of a set of performance measurements that provide context on the system's advancement on predefined intervals and allows the system's stakeholders to assess whether the relevant goals and objectives have been accomplished.

A **key performance indicator** (KPI) is a performance measurement which is calculated upon elements extracted from the system. 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. The former correspond to descriptive characteristics (opinions, properties or traits) often accessed through surveys circulated to relevant responders. The latter correspond to measurable characteristics involving actual gauging.

To enable the calculation of a performance indicator, specific information needs to be gathered from all relevant sources. Any measurable quantity that is utilised as input to the KPI calculation is identified as **performance metric** provided that it indicates some aspect of progression [1]. To guarantee its usability and provide context on questions about the system's performance, a metric needs to be directly measurable (or indirectly determined from other available measurable quantities) and clearly defined in terms of units and range. The performance metrics are built upon raw data derived either from measurements of a system's actual operation or measurements of a system's simulated operation based on modelling approaches.

Within the D^2EPC Human Comfort & Wellbeing indicators, only quantitative KPIs are considered as their calculation is based on acquired data from the pilot IoT infrastructure. The respective metrics are designated as **dynamic**, provided that they are constantly changing over time (timeseries data). According to their measuring interval, they can be segmented into two distinct tiers. Tier 1 metrics deliver a higher-level view of performance based on greater temporal granularity (day, week, month). Tier 2 metrics offer a more detailed context for the system operation as their measuring intervals are compressed to hourly or even sub-hourly. As expected, tier 2 metrics can be converted into tier 1 by aggregation.

The definitions of raw data, tier 1 and 2 metrics and performance indicators constitute a staggered analysis approach. In Figure 1, a conceptual pyramid representation of the multi-tier approach is presented. The raw data obtained from actual measurements, stand on the lowest level. Through a data pre-processing procedure (data manipulation and cleansing), tier 2 metrics can be extracted from raw data and further aggregated into tier 1 metrics or directly imported in the calculation formulas of the KPIs. The performance indicators stand on top of the multi-tier pyramid and drive the system's evaluation in regards to the goals and objectives set for a specific operation. As a result, various stakeholders might be involved in the KPI monitoring and assessment. To eliminate inconveniences and guarantee concrete and robust inference, a set of desirable indicator characteristics has been defined. More specifically, an indicator should be:

- Measurable and feasible, defined upon retrievable metrics measured at reasonable effort/cost
- Understandable, comprehensive and clearly-defined

- Meaningful and relevant, providing valuable insights to the user
- Aggregated on the correct scale
- Unique, not overlapping with the definitions of other indicators
- Interesting, in order to attract the attention of the stakeholders
- Responsive to system changes, meaning that its value can be altered
- Comparable, in cases it's applied on different systems

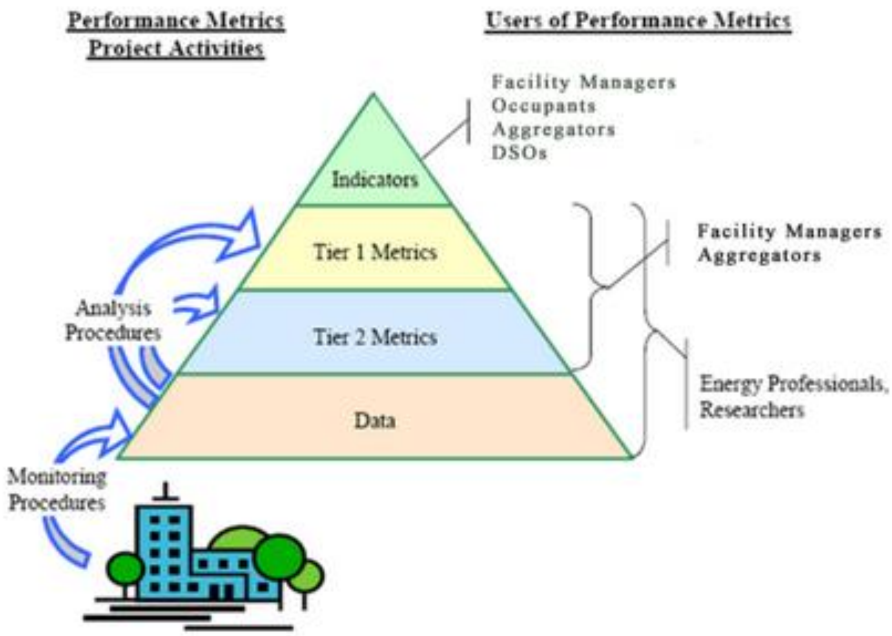

Figure 1. Multi-tier Approach [1]

2.2 Principles of the Methodological Framework

The Human Comfort methodological framework, as envisioned within D^2EPC, sets its grounds on the extraction of user profiles that impact the dynamic building performance. The comfort profiles are defined upon a series of environmental parameters considered critical to the occupant's interaction with the surrounding environment. Due to the dynamic nature of the D^2EPC, the profile extraction is materialised by a **measurement-based** analysis performed on IoT data as collected by sensing infrastructure deployed in the buildings. Through this approach, the comfort profiles acquire the following characteristics:

Data-driven: Specialised statistical models are utilised to detect and analyse the occupant's behavioural patterns on the ambient condition metrics. The comfort profiles are considered personalised as they are adjusted to the user preferences being extracted from previous user behaviour.

Non-intrusive: The profile analysis is solely based on building data streams avoiding further interaction (i.e., provision of extra information) with the occupant. A non-intrusive approach promotes the user's acceptance and overall cooperation within the project.

Dynamic: The comfort profiles can be dynamically recalculated on updated data at predefined intervals. The profiles manage in this way to adapt to system changes and avoid being considered obsolete.

The extracted comfort profiles are then utilised to elicit the Human Comfort indicators. The calculated boundaries act as a basis for the preferred conditions within a building and are further compared with the current building conditions, during the period of interest. The resulting deviations are aggregated and constitute an indication of the building's current performance.

As soon as the indicator values are determined, two different methods for the building's comfort performance evaluation can be implemented, recognised within the measurement-based approach. More specifically:

- **Benchmarking method**: which compares the KPI values among similar and comparable external (i.e., buildings of the same characteristics) or internal (i.e., reference values from space within the same building) systems.
- **Baselining method**: based on which the KPI values are calculated in a previous snapshot (on historical data of the same building) and compared with the current values. The references are periodically updated, subject to the availability of new data. The baselining method will be utilised within T2.2 to monitor the system's progression.

2.3 Hybrid Approach on the HC&W Performance Framework

T2.2 aims to deliver a complete set of behavioural profiles which comprise of:

- the human comfort and wellbeing indicators
- the algorithms and models adapted to extract the indicators, and
- the expected ranges of desired values (per user segment)

The profile extraction will be realised upon the acquisition of building data streams, derived from a deployed sensor network in the D^2EPC pilots, supplementary to their existing IoT infrastructure. The outcome will shed light on the building system utilisation boundaries that lie within the comfort zone of the occupants.

The data-driven approach considered (discussed in section 2.2), steps on historic ambient conditions data to calculate the preferred bottom and upper boundaries based on the user's past behaviour. To achieve this, a Personalised Comfort Profiling Engine (chapter 5), developed by Hypertech, has been updated with state-of-the-art clustering algorithms that identify data patterns in the performance metrics and calculate the desirable boundaries.

The adoption of the profiling engine is determined based on a number of requirements expected to be satisfied. More specifically:

- **Data availability**: The wireless sensor network deployed in the pilots must guarantee the data provision regarding the entirety of the examined performance metrics for the spaces and periods of interest. Considering the environmental nature of the metrics, a year of historic values is a prerequisite in order to address the fluctuations due to the weather conditions (e.g., heating/cooling period)
- **Data quality**: Faulty equipment prone to malfunctions and connection losses may generate inaccurate, incomplete or inconsistent data which is high likely to hinder the profile

extraction. Low data quality is minimized through specialised cleansing algorithms delivered within Hypertech's solution (T3.1).

- **Applicability**: A personalised profile definition is not relevant for the entirety of the performance metrics. Many environmental parameters governing the human wellbeing are not perceived by the occupants (such as toxic gas concentrations). Inference on these parameters cannot be performed on the user's point of view.

A hybrid methodology is employed for the boundary determination of thermal and visual comfort based both on static and dynamic elements. If it's feasible, the comfort profiling engine is utilised. In any other case, building code boundaries obtained from the literature are implemented. Regarding occupant's wellbeing, the corresponding boundaries are obtained directly from European and national standards.

Based on the outcome of the analysis on the HC&W indicators, the engine concerns specific aspects related to the thermal and visual comfort. Regarding the remaining aspects, various European and national frameworks/standards were examined in order to identify proposed limits and methodologies suitable for inclusion in the comfort and wellbeing assessment. According to the literature findings, Level(s) framework was heavily considered which is a common European framework for evaluating the sustainability of buildings (both commercial and residential). Other standards and frameworks have also been considered and they are discussed in the respective KPI sections.

Level(s) has been constituted on the basis of European harmonised standards and delivers several core indicators [2] to be applied from the first stages of a building's design to the end of its life. Hence, this framework can be used both to report the existing situation and improve the performance of the building. Level(s) is based on six macro – objectives presented in Table 1.

Table 1. The definition and scope of each of the Level(s) macro-objectives [2]

Macro-objective		Definition	Scope and focus
Macro-objective 1 **Greenhouse gas and air pollutant emissions along a buildings life cycle**		Minimise the total greenhouse gas emissions along a buildings life cycle[1], from cradle to grave, with a focus on emissions from building operational energy use and embodied energy.	Action at building level with a focus on the objectives of: • Near zero energy consumption during the use phase, supplemented by the contribution of cost effective and low/zero emission energy technologies and infrastructure. • Embodied greenhouse gas emissions along the buildings whole life cycle, including those associated with product manufacturing, maintenance, repair, adaptation, renovation and end of life. In assessing a building's performance, there shall be specific attention paid to the potential trade-offs between embodied emissions and use stage (operational) emissions, in order to enable the minimisation of total greenhouse gas emissions along the life cycle.
Macro-objective 2: **Resource efficient and circular material life cycles**		Optimise the building design, engineering and form in order to support lean and circular flows, extend long-term material utility and reduce significant environmental impacts.	Actions at building level with a focus on material efficiency and circular utility. This shall encompass actions along the life cycle relating to: • building design, • structural engineering and construction management, • construction product manufacturing, • replacement cycles and flexibility to adapt to change, and • the potential for deconstruction. The overall objective shall be to optimise material use, reduce waste and introduce circularity into designs and material choices.
Macro-objective		**Definition**	**Scope and focus**
Macro-objective 3: **Efficient use of water resources**		Make efficient use of water resources, particularly in areas of identified long-term or projected water stress.	Actions at building level, in particular for buildings located in areas of continuous or seasonal water stress. This could combine efficiency measures to minimise water use, as well as supply-side measures such as grey water reuse and rainwater harvesting, designed to make use of alternative sources.
Macro-objective 4: **Healthy and comfortable spaces**		Create buildings that are comfortable, attractive and productive to live and work in, and which protect human health.	Actions at building level to address critical aspects of indoor environmental quality that influence occupier health, comfort and productivity, the first four of which have been identified being: • the quality of the indoor air for specific parameters and pollutants, • the degree of thermal comfort during an average year, • the quality of artificial and natural light and associated visual comfort, and • the capacity of the building fabric to insulate occupiers from internal and external sources of noise.
Macro-objective 5: **Adaptation and resilience to climate change**		Futureproof building performance against projected future changes in the climate, in order to protect occupier health and comfort and to minimise long-term risks to property values and investments.	Actions at building level to adapt and ensure resilience to the following risks: • increased overheating in summer and inadequate heating in winter, which could lead to discomfort and be detrimental to health, • increased risk of extreme weather events, which could compromise the security and integrity of building elements, and • increased risk of flood events, which could overwhelm drainage systems and damage structures and materials.
Macro-objective 6: **Optimised life cycle cost and value**		Optimise the life cycle cost and value of buildings to reflect the potential for long-term performance improvement, inclusive of acquisition, operation, maintenance, refurbishment, disposal and end of life.	Actions and decision-making at building level that are based on a long term view of the whole life costs and market value of more sustainable buildings, including: • achieving lower life-cycle costs and more productive and comfortable spaces to live and work in, and • having a positive influence on property market value appraisals and risk ratings.

Macro – objective 4 “Healthy and comfortable spaces” is relevant to the HC&W indicators as it aims to create comfortable, attractive, and productive buildings to live and work in and protect human health. This macro–objective has the following indicators:

- 4.1. Indoor air quality,
- 4.2. Time outside of thermal comfort range,
- 4.3. Lighting and visual comfort,

The common framework is organised into three levels which correspond to the stage of execution of a building project:

Level 1: The conceptual design, which concerns a qualitative assessment of the concepts that have already been or are expected to be applied.

Level 2: The detailed design, which concerns a quantitative assessment of the designed performance and monitoring of the construction

Level 3: The as-built and in-use performance, which examines how the building performs after the handover to the residents by monitoring the building activity in regards to various parameters, defined within the six macro-objectives.

For the D^2EPC, only Level 3 is considered (testing after occupant entry and furnishing) taking into account the project’s demonstration cases (already occupied for residential or commercial purposes).

The HC&W indicators are part of the dynamic indicators to be delivered within D^2EPC. Their calculation will be materialised through a Dynamic KPI engine integrated in the D^2EPC Calculation Engine (T4.1). The project’s common repository will guarantee the continuous and sufficient real time and historic data provision towards an accurate delivery of the KPI results. Figure 2 provides a conceptual representation of the overall hybrid methodology.

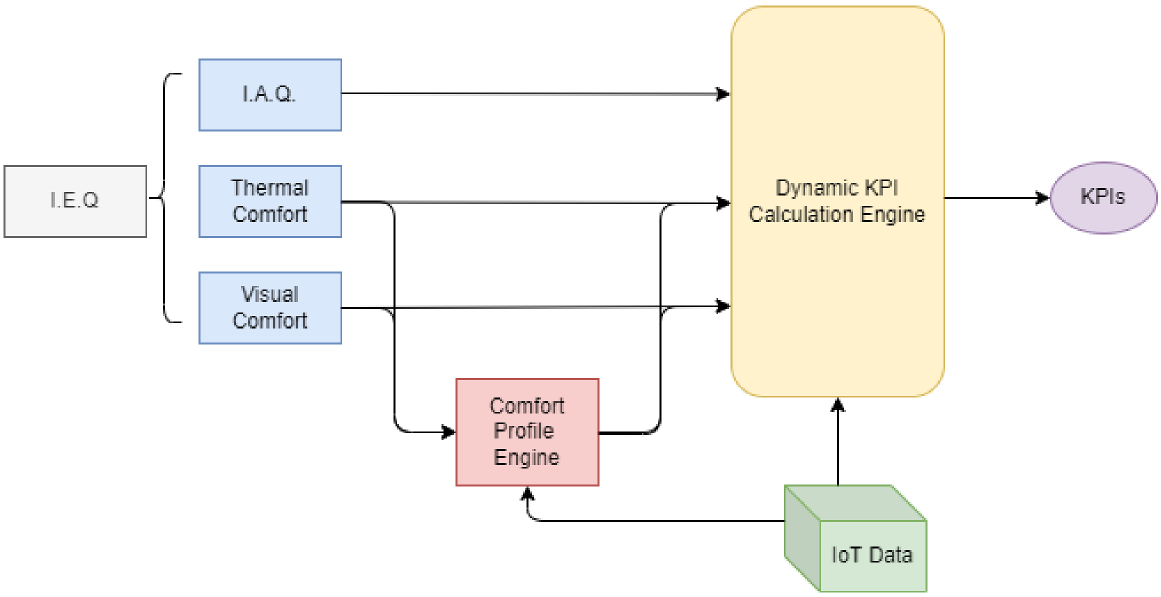

Figure 2. Hybrid methodology of the HC&W Performance Framework

3 D^2EPC Human Comfort & Wellbeing Performance Framework

3.1 Introduction to the Indoor Environmental Quality

The term Indoor Environmental Quality (I.E.Q.) refers to the quality of indoor conditions inside a building which are inextricably linked with the human comfort and wellbeing. A building's overall I.E.Q. is determined by various factors from different domains that influence the occupant's quality of life. These include the indoor air quality (I.A.Q.), the thermal, visual and acoustic comfort, space ergonomics and, as of lately, numerous other factors have been identified relevant to the I.E.Q. such as the water quality, electromagnetic radiation and hygiene.

The indicators defined within this report, focus on the thermal comfort, the visual comfort and the indoor air quality. The three domains are considered of critical importance as they are directly associated with the occupant's health and perception of the building's indoor conditions. An initial approach on the Comfort and Wellbeing indicators proposed the inclusion of the acoustic comfort as well. However, the acoustic comfort is not directly relevant to the building energy efficiency. As it mostly concerns architects and interior designers during the design stage of the building and judging by the demonstration cases which correspond to in-use buildings, acoustic comfort was considered out of scope of the dynamic EPC.

In the following sections, all domains examined are described in terms of definition, relevant literature and approach within the project.

3.2 Thermal Comfort

3.2.1 Thermal Comfort Definition

Thermal comfort is defined as the level of human satisfaction with the existing thermal conditions inside a space. The acceptance of the thermal environment plays a decisive role in the occupant's mood and productivity both in residential and commercial buildings. A properly heated and cooled space further contributes to the human wellbeing especially in places with extreme weather conditions.

Four mechanisms [3] are identified in the human body's thermal energy exchange (Figure 3): The heat loss is caused by:

- **Convection** which corresponds to heat transfer via the displacement of a liquid (air or water molecules across the skin) from one area of the body surface to another.
- **Conduction** which is the transfer of internal energy by microscopic collisions among particles of two objects in close proximity. Consequently, the human body loses thermal energy via contact with surrounding objects.
- **Radiation** which corresponds to the thermal radiation fundamentally emitted from any quantity of matter with temperature above the absolute zero.
- **Evaporation** which corresponds to vaporisation of a liquid from a surface during its transition from the liquid to the gas phase. A wet skin (sweating) or wet clothing can trigger this mechanism.

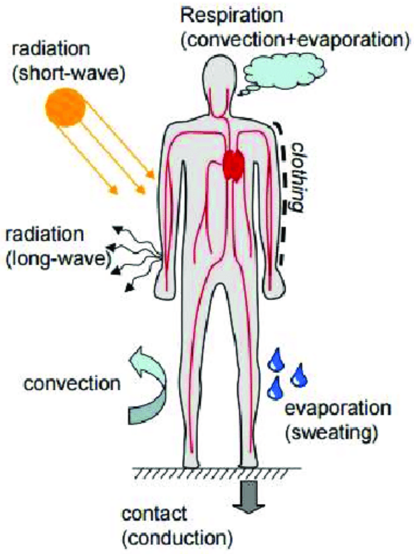

Figure 3. Heat exchange mechanisms of the human body [3]

In indoor spaces with low to medium metabolic rate activities (residences, offices, shops, etc.) the conduction, convection and radiation affect mostly the overall heat loss and, hence, the thermal comfort. In industrial buildings where higher metabolic rate activities take place, the evaporation mechanism is utilised by the human body to remove excess heat.

The most common indoor heat sources correspond to the mechanical and electrical equipment (HVAC systems, lighting, computers), the sun radiation and the human presence. In parallel, the most common sources of cold correspond to windows, thermal bridges in the envelope and low-quality insulation in the walls. The aforementioned significantly influence the thermal environment which may lead to occupant's discomfort. In extreme cases when the heat flow to the human body is excessive, it can lead to serious medical conditions (e.g., heat strokes). On the contrary, when the heat flow is insufficient, serious cold-related injuries are highly likely to occur as well as permanent tissue damage and hypothermia.

Thermal comfort is mostly affected by six factors related to the indoor air, the heat radiation of the surfaces, clothing and activity level. More specifically:

- **Air (dry-bulb) temperature**: The temperature of the indoor air is one of the parameters whose alterations are directly perceived by the occupants. It can be adjusted fairly easy with either passive or mechanical (HVAC) heating and cooling.
- **Mean radiant temperature**: Corresponds to a weighted average temperature from all surfaces that surround a particular point. It is highly dependent on the materials and orientation of the building
- **Air velocity (air flow)**: Relates to indoor air speed and direction. An increase in the air velocity results in higher heat exchange between the occupants and the surrounding air.
- **Relative Humidity**: Measures the amount of moisture of the indoor air. Relative humidity is considered both a comfort and wellbeing parameter.
- **Clothing**: The occupant's individual insulation due to clothing. Higher clothing levels hinder the heat loss.
- **Metabolic heat**: Corresponds to the level of physical activity. Higher activity levels result to greater heat production by the human body.

Combined information on the abovementioned factors provides a holistic view on the occupant's thermal comfort. Unfortunately, not all parameters are measurable in an efficient way. Some of them require sophisticated equipment (i.e., mean radiant temperature and air velocity) while others are mandatorily estimated (clothing and metabolic rate). These constraints have been seriously taken in consideration during the definition of the thermal comfort and wellbeing indicators (section 4.1).

3.2.2 Literature research on Thermal Comfort

The finalised selection of the thermal comfort indicators has been based on a comprehensive study on existing literature addressing the indoor thermal environment. Environmental parameters and reporting methodologies have been obtained from standards and frameworks briefly described below:

DIN EN 15251 – "Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics" [4] that specifies the indoor environment criteria concerning the design, performance and operation of buildings. The standard identifies the main parameters used as input for the energy calculations and long-term evaluation of building as well as the performance metrics recommended by the Energy Performance of Buildings Directive (EPBD) [5] to be used for monitoring and visualising the indoor environment. EN 15251 is mainly applicable in non-industrial buildings (such as apartments, offices and educational building which cover the D^2EPC demonstration cases) where indoor environmental conditions are adjusted based on human occupancy and not industrial processes.

ANSI/ASHRAE 55:2017 – "Thermal environmental conditions for human occupancy" [6] is the American National Standard that provides context on the acceptable conditions governing the indoor thermal environment for different stages of a building's status from design, to commissioning and operation. The scope of the standard covers the environmental and personal factors (temperature, humidity, air speed, radiant effects, activity and clothing) and specifies the optimal thermal conditions suitable for healthy adults occupying indoor spaces at atmospheric pressure equivalent to altitudes up to 3000m, for periods greater than 15 minut8 es.

EN ISO 7243:2017 – "Ergonomics of the thermal environment. Assessment of heat stress using the WBGT (wet bulb globe temperature) index" [7] is one of the series of standards addressing hot, moderate and cold environments. It focuses on the Wet Bulb Globe Temperature which corresponds to an index that evaluates the presence or absence of heat stress. The scope of the standard covers the heat exposure of an individual during the course of a working day (~8h). It can be applied both in outdoor and indoor occupied spaces by adults eligible to work.

Level(s) 4.2 – "Time outside thermal comfort" [8] is the indicator delivered by Level(s) framework to measure the total amount of time during which the occupants are satisfied with the building's indoor thermal condition on a yearly basis, examined separately for the heating and the cooling period. The activities related to each level are presented in Table 2.

Table 2. Level(s) 4.2 indicator activities per level [8]

Level	Activities related to indicator 4.2
1. Conceptual design	✓ Integrate risk assessment into the design of the building ✓ Deliver solutions for renovation
2. Detailed design and construction (based on as-built drawings)	✓ Building permitting assessment towards avoiding overheating ✓ Further examination of thermal comfort aspects (e.g., localized discomfort)
3. As-built and In-use performance	✓ Building energy performance assessment with climate and activity normalisations ✓ Commissioning ✓ Comparison between estimated satisfaction and occupants' feedback (based on surveys)

3.2.3 D^2EPC Approach on Thermal Comfort

ASHRAE 55:2017 provides a recommended boundary for the indoor air temperature ranging from 19,4 to 27,7 ^{O}C. Narrowed down boundaries can be calculated from Predictive Mean Vote/Predicted Percentage of Dissatisfied (PMV/PPD) and adaptive model methodologies (for mechanically and naturally ventilated buildings respectively), also supported by the standard. Within the context of D^2EPC, the two methodologies are considered out of scope. Both require measurements of the mean radiant temperature realised by sophisticated equipment which is not always acceptable from the residents. In addition, other input parameters (such as clothing or metabolic rate) are estimated based on surveys circulated to the occupants. This approach increases the overall intrusiveness contrary to the pure data-driven approach envisioned.

Thermal comfort, in the majority of times, is considered a rather subjective concept given that all individuals have, to an extent, a distinct reaction to the thermal environment. Provided that even smaller fluctuations in the air temperature are directly perceived by humans, it is taken for granted that occupants will eventually proceed to specific actions (i.e., adjust the setpoint temperatures in the thermostats, open/close windows) in order to maintain the air temperature according to their preferences. Automatically, it can be inferred that occupants' previous behaviour, imprinted on historic data, constitutes an indication on the preferred boundaries. These alternative boundaries are extracted from the personalised comfort profiling engine which is applied on preceding data to deliver upper and bottom air temperature limits per timestamp for the course of a day. If that's not feasible, the boundary from ASHRAE 55:2017 will be considered.

3.3 Visual Comfort

3.3.1 Visual Comfort Definition

Visual comfort is expressed as the level of human satisfaction with the visual environment. Many everyday tasks in residential or working spaces are carried out much more efficiently, provided that a sufficient but not excessive amount of luminous intensity is supplied. 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.

The most critical factors [9] influencing the occupant's visual comfort are presented below:

- **Illuminance**: The amount of light (in lumen) that hits a surface. The illuminance level is the first and most critical parameter examined in regards to visual comfort. Low illuminance levels have been correlated with headaches, eyestrains, neck and back issues (from straining), accidents and even depression. The brightness of surfaces where working tasks are performed needs to be maintained above specific limits dictated by European and national standards.
- **Glare**: When the brightness of a light source within the occupant's field of view is significantly greater than the brightness of the surroundings the glare effect occurs. Glare makes it difficult to the occupant to distinguish between an object against the background which causes great irritation and potentially eye strain.
- **Daylight provision:** A sufficiently illuminated space purely based on sunlight provides the optimal visual conditions to the occupant. Daylight is more relaxing to the eyes than artificial light sources and raises the mood to the user.
- **Colour rendering:** The ability of a light source to render colours correctly. Daylight is considered the reference point for the optimal colour rendering. The better the artificial light source the more it approaches daylight's colours.

3.3.2 Literature Research on Visual Comfort

The literature study that acted as a basis for the final definition of the visual comfort indicators comprises of several European and national standards briefly described below

EN 12464-1:2021 – "Light and lighting. Lighting of work places Indoor work places" [10] delivers the best practices towards a balanced indoor lighting and specifies the requirements for lighting solutions in terms of quality and quantity of illumination. It aims to stimulate the designers to consider all light sources (both artificial and natural) within a space by recognising the importance of daylight provision to the energy efficiency of the building. The scope of the standard covers all usual visual tasks in work places and associated areas and all occupants with normal ophthalmic capacity.

EN 17037:2018 – "Daylight in Buildings" [11] aims to examine the aspects of daylighting design towards an adequate occupant's impression of indoor light and outdoor view from a subjective perspective. The standard provides information on the metrics evaluating the daylight conditions along with the calculation and verification methodologies that determine the variability of daylight over a course of year. The scope of EN 17037 covers the majority of regularly occupied indoor spaces for extended periods of times. Out of scope are considered spaces which carry out activities that are inversely affected by daylighting. The parameters examined within the standard correspond to the daylighting provision, the outdoor view, sunlight exposure and glare.

Level(s) 4.3 – "Lighting and Visual comfort" [9] aims to provide insight towards improving and optimising the indoor visual comfort conditions also taking into consideration the positive effects of the natural lighting in the mood and performance of the occupants. The indicator delivers the specifications of the indoor electric lighting equipment that achieves sufficient quantity and quality of light. It further addresses the daylighting of internal spaces by examining the building geometry and plan depth of the individual spaces. Level(s) 4.3 indicator is currently specified with instructions for users at level 1 (design stage).

3.3.3 D^2EPC Approach on Visual Comfort

Apart from the illuminance, the rest of the visual comfort parameters (presented in subsection 3.3.1), cannot be measured directly with an all-in-one smart sensing device. Glare demands luminance meters and HDR cameras [12] in order to identify glare sources. The daylight availability cannot be inferred via plain measurements. Colour rendering [13] requires a test-colour method using filters to examine the colour shifts on objects. Inference on the above parameters is provided via modelling simulations of the space and are more relevant during the design stage of the building. This procedure is not relevant for inclusion in the D^2EPC where a measurement-based approach is implemented in order to extract comfort profiles in a purely data-driven manner. As the Illuminance is the most fundamental visual parameter directly perceivable by the occupants, the focus has been gathered on quantifying the visual comfort performance based on the illuminance levels in indoor areas. Furthermore, provided that the occupants proceed to adjust the illuminance of the indoor environment to a preferred level through several actions (e.g., switching on/off lights) the personalised visual comfort boundaries can be estimated through the profiling engine applied on preceding illuminance data. If that's not feasible, recommended boundaries from EN 12464-1:2021 will be applied (section 4.3)

3.4 Indoor Air Quality

3.4.1 Indoor Air Quality Definition

Indoor air quality (I.A.Q.) matters extremely since we spend most of our time indoors; we live, work, learn, entertain ourselves and even travel in enclosed environments. According to Environmental Protection Agency (EPA) (1989), people in developed countries, on average, spend more than 90 percent of their time indoors (approx. 20 hours per day) [14]. Furthermore, it is reported that concentrations of some pollutants indoors are often 2 to 5 times higher than typical outdoor concentrations [15]. The reason for this is that indoors we have pollutants that come from outdoors and pollutants that are emitted inside the building by construction materials, occupants, and their activities. Consequently, we have a situation where high concentrations of pollutants are accumulated in an enclosed environment.

Poor indoor air quality (IAQ) affects occupants' health, productivity, and comfort. It is reported that health effects associated with indoor air pollutants include irritation of the eyes, nose, and throat, which can cause headaches, dizziness, fatigue, as well as various respiratory diseases, heart disease, and cancer. Health effects might vary between the regions of the world. While developing countries deal with health problems caused by burning biomass and other health effects such as respiratory infections, chronic obstructive pulmonary disease, and lung cancer, developed countries deal with allergies, hypersensitivity reactions such as Sick Building Syndrome (SBS), and multiple chemical sensitivity and respiratory infections [16]. There are sufficient links between indoor air pollutants and health effects [15-22]. For example, radon and environmental tobacco smoke (ETS) is the leading cause of lung cancer [17]; dust mites, mould, pet dander, environmental tobacco smoke, particulate matter, and others are "asthma triggers" [18]. Special concern should be taken to children and elderly exposures to volatile organic compounds (VOCs). On the one hand, children are more vulnerable to toxic compounds because they have a higher exposure per kilogram of body weight and are less developed immunologically, physiologically, and neurologically [19]. On the other hand, the elderly may be more exposed to air pollutants than the rest of the population since they spend more time indoors [20].

Furthermore, it is important to emphasise that occupants indoors are exposed to a mixture of pollutants, which is an additional concern. The study of Allen et al. [21] showed that occupants had a lower cognitive function when higher total VOC concentrations were measured. It is also reported that higher quality of air indoors (low pollutant concentration or higher ventilation rate) can lead to a productivity improvement of 3-7 percent according to Wargocki et al. [22] and 10-15 percent according to Clements-Croome et al. [23]. The health effects mentioned above imply that adequate decisions should be made regarding indoor control of pollutant concentrations.

Additionally, the sector of buildings has changed significantly during the past decades, and due to energy efficiency regulations, more airtight buildings are being constructed nowadays. Therefore, the technologies of ventilation (dilution of pollutants) have to be applied to have a high quality of air indoors; otherwise, pollutants will be accumulated and will have a negative impact on building occupants' health, productivity, and comfort. However, installing a ventilation system does not always mean that high IAQ levels will be ensured – ventilation systems can be poorly controlled and maintained [24], or building materials, household products, and occupant activities that emit pollutants can raise problems during construction or exploitation of the building [25]. Therefore, ventilation systems sometimes should not be the only strategy used. A study by Ciuzas et al. [26] showed that high IAQ in buildings could be achieved by wisely combining ventilation and additional filtration techniques of indoor air quality control; pollutant removal efficiency can increase by 20% by using these techniques.

Increased airtightness of buildings has a chain effect on the amount of pollutants in the building and human health. Speaking about a wide variety of pollutants, pollutant monitoring technologies should play a significant role in the near future as technologies of lower-cost sensors evolve fast [27]. The question to be answered is “which pollutant concentrations to measure?”. Moreover, the past decades showed increased awareness of indoor environments’ quality not only by academia and professionals but also by people, who are now more aware of the impact of health and well-being on our quality of life [28].

3.4.2 Literature Research on the Indoor Air Quality

There is a list of standards and recommendations related to IAQ. The World Health Organization (WHO) issued guidance in 2010 on “Selected Pollutants” [29] for public health professionals involved in the prevention of health risks, as well as for professionals and other stakeholders involved in the design and use of buildings and their materials and products. The main objective of the guidance provided is to protect public health from the risks that may arise from various indoor airborne chemicals. The document addresses the most common chemicals that may be present in indoor air and may have negative effects on the occupants’ health if the concentrations of pollutants exceed the recommended values. The results of a comprehensive analysis carried out by a group of experts provide a detailed definition of selected pollutants, which are the followings:

- Benzene
- Carbon monoxide
- Formaldehyde
- Naphthalene
- Nitrogen dioxide
- Polycyclic aromatic hydrocarbons
- Radon
- Trichloroethylene
- Tetrachloroethylene

The guidelines also describe the sources and pathways of exposure to pollutants and their impact on the occupants’ health. The authors propose a health risk assessment and guidelines for safe exposure levels to the above-listed pollutants. Reference to the guidelines delivered by WHO can also be found in the EN standards series, i.e. EN 16798:2019.

The European Standard *“Energy performance of buildings – Ventilation for buildings – Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustic – Module M1-6*” [30] is the first part of standard series EN 16798:2019. Standard EN 16798-1:2019 proposes general requirements and default input values for the use where national regulation is unavailable or does not cover the specific area of interest. Annex B of standard EN 16798-1:2019 proposes specific parameter values for all three of the above methods as well as design values for the indoor CO2 concentration. The standard is supplemented with WHO health-based criteria for indoor air. The suggested guideline defines air requirements for pollutants such as formaldehyde, radon, benzene, etc. Indicators such as ventilation airflow rate, CO2 indoors, formaldehyde and radon concentration, and particulate matter that were proposed and defined in the standard were considered relevant parameters to indicate indoor air quality.

Standard CEN/TR 16798-2:2019 [30] defines the usage and application of the standard EN 16798-1 and gives additional background information. Additionally, CEN/TR 16798-2:2019 is enhanced with information and topics regarding the evaluation of indoor environmental quality, including IAQ indicators and proposed parameters values in different scenarios and use cases. Different categories of criteria are proposed, taking into account the type of building, occupants, as well as climatic and national differences. The standard also provides recommended IAQ indicators parameters’ values, which are presented and listed in Annex B. Proposed values can be selected considering the adaptation type of the occupants, type of building or space, as well as expectations that occupants might have.

ANSI/ASHRAE Standard 62.1-2019 "Ventilation and Acceptable Indoor Air Quality" [31] is the American National Standard for Ventilation and Indoor Air Quality, which responds to increasing knowledge, experience, and research on indoor air quality and its parameters. Despite changes over the years, the main objective of the standard has not changed. The standard aims to establish minimum ventilation rates and related parameters to ensure acceptable indoor air quality and avoid adverse health effects on occupants. Together with various parameters to ensure a safe and healthy indoor environment, the standard provides guidelines for calculating and evaluating ventilation rates in buildings or spaces according to their type and occupancy categories.

Considering residential buildings, *ANSI/ASHRAE Standard 62.2-2019 "Ventilation and Acceptable Indoor Air Quality in Residential Buildings"* is developed particularly for residential buildings with the scope of defining the minimum requirements to achieve acceptable IAQ. The standard describes requirements directed to air quality and includes requirements for the performance of building ventilation systems and their components. The standard shall be addressed for all the types of ventilation systems, i.e., mechanical, natural, or hybrid.

Level(s) - Indicator 4.1 covers three Levels. Activities related to each Level are presented in Table 3. Level and activities related to indicator 4.1

Table 3. Level and activities related to indicator 4.1 [32]

Level	Activities related to indicator 4.1
1. Conceptual design	✓ Design of the building fabric and ventilation systems to meet target ventilation rates ✓ Control of potential sources of humidity by ventilation design ✓ Inspection of properties to be renovated in order to identify any problems relating to dampness and mold. ✓ Design solutions for identified areas of cold bridging and damage from humidity in renovated properties ✓ Source control of target pollutants by a selection of construction products/materials according to their tested emissions.
2. Detailed design and construction (based on as-built drawings)	✓ Verification that as-built and installed building fabric and services reflect those as designed.
3. As-built performance	✓ In-situ measurement of the indoor concentration of target pollutants after completion and handover but prior to occupation. ✓ Functional performance testing of ventilation filters and their suitability for the building location.
3. In-use performance (testing after occupant entry and furnishing)	✓ In-situ measurement of the indoor concentration of target pollutants during the occupation. ✓ In-situ measurement of the CO2 and relative humidity levels.

Level 1 – conceptual design. The aim of the Level 1 is to raise awareness of three highly relevant design aspects that represent the main factors influencing IAQ and contributing to ventilation strategy

optimization. Users should be able to describe if Level 1 aspects were considered or not during the design stage.

Level 2 – detailed design and construction (based on as-built drawings). The aim of the Level 2 is to inform about decisions on the methodological approach to calculate the ventilation rates needed in the different building zones.

Level 3 – as-built and in-use performance (testing after occupant entry and furnishing). The aim of the Level 3 is to allow users to assess IAQ objectively based on the performance of a constructed building. In Level 3, a two-pronged approach is presented. The first approach is an objective one, based on measurements at two stages:

1) after construction but before the occupation, which allows direct comparison to design estimates for ventilation rates and the baseline to be set for CO2, humidity, VOC, and other pollutants.
2) during the occupation, which allows capturing any additional impacts on IAQ caused by occupants, installation of equipment, and furniture.

To have a more comprehensive view, the second approach – subjective one – is used, as testing of IAQ only provides partial information and may not correlate to occupants' perception of IAQ. Subjective evaluation is based on occupants' surveys.

3.4.3 D^2EPC Approach on the Indoor Air Quality

After analysing scientific publications, research results related to IAQ, standards, and recommendations related to the field and Levels framework, key performance indicators (KPIs) for IAQ have been analysed and selected for the D^2EPC. However, taking into consideration the findings of T3.1 [33] which concerns the IoT equipment installations in the D^2EPC pilots, only a portion of the air quality metrics has been deemed measurable due to several limitations regarding the sensing devices. More specifically, based on an extensive market research performed on the available off-the-shelf IoT equipment addressing air quality, it was concluded that such measurements entail the need for multiple installations of distinct smart devices that may end up being highly intrusive with prohibitive cost which surpasses the scope of D^2EPC. For this reason, a subset of the defined KPIs will be utilised for the I.A.Q. assessment (section 4.4).

4 Analysis of the Human Comfort and Wellbeing Performance Indicators

4.1 Long term evaluation of the general comfort conditions

Based on the findings on the literature research, three methodologies are utilised to infer the comfort performance, the “Time out of range”, the “Degree hours” and the “Footprint of Indoor Environment” presented below:

- Level(s) 4.2 indicator, calculates the % of hours during which the occupants are out of comfort for a specific period of interest (e.g., heating/cooling periods in a yearly basis). The comfort limits in the D^2EPC approach are substituted with the personalised boundaries extracted from the comfort profiling engine (where feasible). The resulting percentage value corresponds to the building’s performance of the examined period and acts as basis for the evaluation of progress during the upcoming periods.
- The Degree Hours is a methodology obtained from EN 15251 which integrates tailored weights to the “time out of range” calculation addressing how much the indoor ambient conditions deviated from the recommended conditions. The weights are defined based on the absolute difference between the measured value and the recommended upper or bottom limit.
- The “Footprint of Indoor Environment” from CEN/TR 16798-2 (*ANNEX G – Examples of classification and certification of the indoor environment*) is utilised to address the indicators formed on limits/categories presented in Table 4.

Table 4. Classification by “footprint” of the indoor environment [34]

Quality of indoor environment in % of time of occupancy in four categories				
Percentage	5	7	68	20
Thermal Environment	IV	III	II	I
Percentage	7	7	76	10
Indoor Air Quality	IV	III	II	I

4.2 Selection of the Thermal Comfort KPIs

The works conducted towards the definition of the thermal comfort indicators, initially focused on the environmental parameters selected for the personalised profile extraction. Air (dry-bulb) temperature is the most fundamental factor of the indoor ambient conditions and one of the widely established performance metrics for the quantification of thermal comfort.

Another critical ambient parameter is the relative humidity influencing the occupants in terms of comfort and wellbeing. Higher values of humidity combined with higher temperatures within a space, significantly increase the heat stress. Meanwhile, low humidity values are translated to a dry atmosphere causing disturbance in breathing and eye-sight. In the context of D^2EPC, the relative humidity is addressed both separately and alongside the air temperature considered simultaneously a thermal and indoor air quality performance metric.

Both the air temperature and relative humidity are well-defined metrics, accurately measurable with non-intrusive, easily accessible and relatively cheap smart equipment. Furthermore, the majority of the D^2EPC pilots are already equipped with IoT infrastructure which covers the provision of both measurements. As a result, strong focus was placed in the integration of the two parameters in the HC&W KPI framework.

The combined effect of air temperature and relative humidity is expressed via two thermo-physiological parameters, the “Wet Bulb Globe Temperature” and the “Humidex”. Both WBGT and Humidex are utilised as separate performance metrics and determined indirectly through specific conversion formulas (presented in ANNEX A) which take as input the air temperature and relative humidity measurements.

The WBGT was originally utilised by national weather services to measure the heat stress in direct sunlight during the cooling period, taking into account the temperature, humidity, wind speed, sun angle and cloud coverage. ISO 7243:2017 provides an approximation of the WBGT calculation formula based on the dry and wet bulb temperatures, suitable for indoor spaces. Taking into account the metabolic rate of activities carried out in various commercial and tertiary premises, the standard further delivers the recommended WBGT limits, indicating the acceptable values per workload ranges (Table 5). The respective indicator “Deviation from the acceptable WBGT levels” is formed on these limits. The Wet Bulb Globe Temperature was considered relevant for inclusion in the D^2EPC taking into account the demonstration case housing a metalworking company.

Table 5. Wet Bulb Globe Temperature categories based on [7]

Work Category	Metabolic Rate (Watts)	Examples
Rest	115	Sitting
Light	180	Sitting, standing, light arm/hand work and occasional walking
Moderate	300	Normal walking, moderate lifting
Heavy	415	Heavy material handling, walking at a fast pace
Very Heavy	520	Pick and shovel work

% Work	Workload			
	Light	Moderate	Heavy*	Very Heavy*
75 to 100% (Continuous)	28.0°C	25.0°C	N/A	N/A
50 to 75%	28.5°C	26.0°C	24.0°C	N/A
25 to 50%	29.5°C	27.0°C	25.5°C	24.5°C
0 to 25%	30.0°C	29.0°C	28.0°C	27.0°C

Humidex is the second examined thermo-physiological parameter that fuses temperature and humidity into one quantity. It is utilised by Canadian meteorologists to describe the thermal feeling of a person in outdoor environment based on dew point and air temperature. According to an Australian study [34], Humidex can be applied into indoor environments as a good thermal comfort predictor in humid situations. The Humidex metric, contrary to the WBGT, is accompanied by specific categories regarding comfort, discomfort, heat distress and danger for the occupants and has been integrated in the KPI framework to provide a clearer view on the combined effect of air temperature and relative humidity on thermal comfort. These categories are utilised for the definition of the respective “Humidex levels” indicator. Finally, Humidex has been previously examined exclusively during the cooling period but within D^2EPC, the heating period will be examined as well.

The outcome of the analysis on the thermal comfort indicators resulted in five indicators presented below:

Table 6. Thermal Comfort Indicators

Indicator Name	Indicator Description	Units
Deviation from the temperature range	Calculates the % of hours (during which the building is occupied) when the temperature is outside a specified range from the personalized comfort boundaries (EN 15251) compared to the number of hours of the period of interest. The scope of the indicator concerns both residential and commercial buildings	%
Thermal Degree Hours	The time during which the actual temperature exceeds the personalized range (occupied hours) is weighted by a factor which is a function depending on by how many degrees, the range has been exceeded (EN 15251). The scope of the indicator concerns both residential and commercial buildings	numeric
Deviation from the humidity range	Calculates the % of hours (during which the building is occupied) when the relative humidity is outside a specified range from the personalized comfort boundaries (EN 15251). The scope of the indicator concerns both residential and commercial buildings Humidity boundary: [40-60%] (level(s))	%
Deviation from the acceptable WBGT levels	Calculates the % of hours (during which the building is occupied) when the thermo-physiological parameter 'Wet-Bulb Global Temperature' (as defined in ISO 7243:2017) is greater than a specified value based on the workload and metabolic rate. The scope of the indicator concerns commercial buildings where heavy tasks of high workload and human metabolic rate take place during the heating period. A specific threshold is applied per case.	%
Humidex levels	The Humidex is thermo-physiological parameter (defined in ISO 7243:2017). The indicator is reported based on the % of hours of each level compared to the total hours of the period of interest. The scope of the indicator concerns both residential and commercial buildings. Humidex levels Leve I: 20 to 29 -> Little to no discomfort Leve II: 30 to 39 -> Some discomfort Leve III: 40 to 45 -> Great discomfort Leve VI: Above 45 -> Dangerous	%

Detailed description, units, calculation methodologies, relevant metrics, spatial granularity and measuring intervals of the thermal indicators are presented in ANNEX A of the deliverable.

4.3 Selection of the Visual Comfort KPIs

The definition of the visual comfort indicators has followed an analogous procedure to the thermal comfort definition. However, different approaches in the context of illuminance boundaries are proposed, based on the building typology and type of space activity

Contrary to the air temperature, the illuminance metric patterns are characterised by significant fluctuations during the course of the day. Daylight provision is highly dependent on the angle of incidence of the incoming outdoor light. As a result, the illuminance values (over a 24h course) acquired from sensing equipment may extend to up to three orders of magnitude based on the sensor placement and time of day. The extreme values observed concern only a specific area of the examined space (the surface of the sensor) and are not always indicative of the overall space illumination. Therefore, the upper personalised boundaries have been deemed out of scope, further taking into consideration their relation to natural (but not artificial) light which is not correlated with building energy consumption. On the other hand, the bottom boundaries have been integrated into the analysis as they correspond to the minimum acceptable illuminance levels by the occupants. Cloudy days significantly affect the daylight provision which might trigger the occupants to adjust the illuminance levels. In non-daylight hours, the overall illumination of a space is purely dependent on the artificial lighting to support various activities. The outcome of the occupants' actions indicates the minimum acceptable illuminance levels (per timestamp of the day) which are further utilised to examine the visual comfort performance in the space of interest.

Based on the above, the personalised comfort profiling engine is deemed relevant to regularly occupied spaces by the same individuals towards rationalising a visual comfort assessment on preceding data. Considering the D^2EPC demonstration cases, only residences fall under the scope of personalised profiling. The rest of the pilots comprise of spaces with different occupants throughout the day and diverse activities (classrooms, cafeteria, lecture halls, production halls). The recommended amount of available light in such commercial premises is dictated by standards and frameworks which deliver illuminance levels during occupancy hours, tailored to various working activities. In Table 7, the recommended illuminance levels per difficulty of visual activity along with the corresponding areas are presented as obtained from EN 12464-1. In residential cases where the comfort profiling engine is not applicable (low-quality or insufficient provision of past data), casual seeing is assumed.

Table 7. Recommended illuminance levels based on activity and area [10]

Illuminance (lux)	Activity	Area
100	Casual seeing	Corridors, changing rooms, stores
150	Some perception of detail	Loading bays, switch rooms, plant rooms
200	Continuously occupied	Foyers, entrance halls, dining rooms
300	Visual tasks moderately easy	Libraries, sports halls, lecture theatres.
500	Visual tasks moderately difficult	General offices, kitchens, laboratories, retail shops.
750	Visual tasks difficult	Drawing offices, meat inspection, chain stores.
1000	Visual tasks very difficult	General inspection, electronic assembly, paintwork, supermarkets.
1500	Visual tasks extremely difficult	Fine work and inspection, precision assembly.
2000	Visual tasks exceptionally difficult	Assembly of minute items, finished fabric inspection.

Other parameters of visual comfort (i.e., glare, daylight provision and outdoor view) have been deemed out of D^2EPC scope as they do not correspond to the building's operation and are therefore irrelevant to the dynamic EPC focus of the project. Furthermore, extra information provision or sophisticated equipment installations expected by the building stakeholders, might not be feasible. The overall comfort performance is envisioned to be determined through a data-driven, non-intrusive methodology which eliminates the dependence on the occupant's involvement, compliance and acceptability.

The outcome of the analysis on the visual comfort indicators resulted in four indicators presented below:

Table 8. Visual Comfort Indicators

Indicator Name	Indicator Description	Units
Deviation from the set Illuminance boundary	Summation of all the daylight hours of a regularly occupied space during which the illuminance was lower than the profiling engine bottom boundary, compared to the total hours of the period of interest. The scope of the indicator concerns residential buildings taking into consideration that the occupant's visual comfort during home activities is purely subjective	%
Deviation from the standard Illuminance levels	Summation of all the daylight hours of a regularly occupied space during which the illuminance was lower than the acceptable levels determined within EN 12464, compared to the total hours of the period of interest. The scope of the indicator concerns commercial buildings where the illuminance levels for different spaces and activities must adhere to international standards. Within D^2EPC, the illuminance levels for different spaces from EN 12464, are utilised.	%
Set Visual Degree Days	The daylight hours during which the space is occupied and the measured illuminance remains below the profiling engine bottom boundary. The calculation is weighted by a factor which is a function	%

	depending on by how many degrees the average hourly illuminance was below the bottom boundary (EN 15251). The scope of the indicator concerns residential buildings taking into consideration that the occupant's visual comfort during home activities is purely subjective	
Standard Visual Degree Days	The daylight hours during which the space is occupied and the measured illuminance remains below the building code level provided within EN 12464. The calculation is weighted by a factor which is a function depending on by how many degrees the average hourly illuminance was below the acceptable level. The scope of the indicator concerns commercial buildings where the illuminance levels for different spaces and activities must adhere to international standards. Within D^2EPC, the illuminance levels for different spaces from EN 12464, are utilised.	%

Detailed description, units, calculation methodologies, relevant metrics, spatial granularity and measuring intervals of the visual indicators are presented in ANNEX B of the deliverable.

4.4 Selection of the Indoor Air Quality KPIs

This task aims to identify indicators that impact the overall dynamic building performance mainly from the user's comfort and well-being. This section provides detailed specifications of the selected IAQ comfort KPIs. More specifically, it delivers the indicator names, descriptions and the necessary input metrics for the calculation.

After the desk research (scientific papers and standards related to IAQ), for D^2EPC project IAQ KPIs identification, the Level(s) framework was adopted. Level(s) indicates that different parameters can be measured for indicator 4.1 "Indoor air quality", and these parameters are presented in Table 3. For measurement and calculation procedures of different parameters related to IAQ indicators, Level(s) refers to EU standards [32].

Table 9. Parameters covered by indicator 4.1 "Indoor air quality" [32]

4.1.1 Indoor air quality conditions		**4.1.2 Target pollutants**			
		Mainly from indoor sources		**Mainly from outdoor sources**	
Parameter	**Unit**	**Parameter**	**Unit**	**Parameter**	**Unit**
Ventilation rate (air flow)	$L/s/m^2$	Total VOCs	$\mu g/m^3$	Benzene	$\mu g/m^3$
CO_2	ppm	CMR VOCs	$\mu g/m^3$	Radon	Bq/m^3
Relative humidity	%	R value	Decimal ratio	Particulate matter <2,5 µm	$\mu g/m^3$
Occupant survey	Not defined	Formaldehyde	$\mu g/m^3$	Particulate matter <10 µm	$\mu g/m^3$

The activities related to each Level covered by indicator 4.1 are presented in Table 2. For the D^2EPC project, we suggest considering Level 3 – as-built and in-use performance (testing after occupant entry and furnishing). Level 3 provides target indoor air pollutants presented in Table 10. Target indoor air pollutants for Level 3

Table 10. Target indoor air pollutants for Level 3 [32]

Nature of IAQ parameter	IAQ parameter
Pollutants predominantly from outdoor sources	Radon (Bq/m^3)
	PM2.5 (µg/m^3)
	PM10 (µg/m^3)
	Ozone (µg/m^3)
	Benzene (µg/m^3)
Air quality aspects (from outdoor & indoor sources)	Relative humidity (%)
	CO2 (ppm indoors)
	CO2 (ppm outdoors)
Pollutants predominantly from indoor sources	Total VOC (µg/m^3)
	Total CMR VOCs (µg/m^3)
	R-value
	Formaldehyde (µg/m^3)

For the D^2EPC project, the list of IAQ KPIs was created according to Level(s) and parameters (metrics) covered by indicator 4.1 "Indoor air quality". Indicators are presented in Table 11.

Table 11. IAQ KPIs according to Level(s)

Indicator	Indicator Description	Units
Ventilation rate (airflow)	The ventilation rate is the magnitude of outdoor airflow to a room or building through the ventilation system or device.	L/s/m^2
Total Volatile Organic Compounds (TVOCs)	TVOC is the sum of the concentrations of the identified and unidentified volatile organic compounds in the indoor air.	µg/m^3
Benzene	Benzene concentration in the indoor air.	µg/m^3
CO_2 indoors	CO2 concentration in the indoor air.	ppm
Formaldehyde	Formaldehyde concentration in the indoor air.	µg/m^3
Radon	Radon concentration in the indoor air.	Bq/m^3
Particulate matter <2,5 µm (PM 2.5)	Particles' that are 2,5 µm in diameter or smaller concentration in the indoor air. According to EN 16890-1, a particulate matter passes through a size-selective inlet with a 50% efficiency cut-off at 2.5µm aerodynamic diameter.	µg/m^3
Particulate matter <10 µm (PM 10)	Particles' that are 10 µm in diameter or smaller concentration in the indoor air.	µg/m^3

	According to EN 16890-1, a particulate matter passes through a size-selective inlet with a 50% efficiency cut-off at 10µm aerodynamic diameter.	

The air quality KPIs are formed on the following limits/categories:

- The ventilation rate categories (for diluting all emissions from the building) are presented according to CEN/TR 16798-1:2019. The ventilation rate can be estimated on a daily basis at specific timestamps and then averaged for the period of interest. The estimation of ventilation rate is challenging due to several assumptions (e.g., no other CO_2 sources other than occupants). It is further influenced by many factors which may generate even worse results. In mechanically ventilated buildings, actual ventilation rates may be acquired by sensors of the ventilation system.
- The limits for total volatile organic compounds (TVOC) (the sum of the concentrations of the identified and unidentified volatile organic compounds in the indoor air) are given according to EN 16798-1, 2019.
- The limits for Benzene concentration indoors are given according to EN 16798-1.
- The CO_2 concentration categories are given according to CEN/TR 16798-1/2:2019. CEN/TR 16798 defines four distinct categories for the differences between indoor/outdoor CO_2 concentrations.
- The limits of formaldehyde concentration in the indoor air are given according to EN 16798-1.
- The limits of radon are given according to WHO.
- The limits of PM 2.5 and PM 10 are given according to EN 16798-1.

Measuring and presenting data for all identified KPIs would give a comprehensive view of the current IAQ in the building and potential for improvement. However, within the D^2EPC project, strong focus will be placed on three IAQ KPIs to be selected for the representation of the user's well-being point of view, in accordance with the findings of T3.1 which shed light on the measurability of I.A.Q. performance metrics:

- CO_2 indoors,
- TVOC (the sum of the concentrations of the identified and unidentified volatile organic compounds in the indoor air),
- PM 2.5 (particulate matter <2,5 µm).

The remaining indicators are considered as complementary.

Detailed description, units, calculation methodologies, relevant metrics, spatial granularities and measuring intervals of the I.A.Q. indicators are presented in ANNEX C of the deliverable for the entirety of identified I.A.Q. KPIs. ANNEX C1 presents the main I.A.Q. indicators addressed within D^2EPC while ANNEX C2 includes the complementary I.A.Q. indicators. Lastly, regarding the methodology for the reporting of I.A.Q. indicators, the "footprint" classification will be utilised, considering the fact that all air quality KPIs are formed on the aforementioned limits/categories.

5 Personalised Comfort Profiling Engine

5.1 Comfort Profiling Engine Specifications

5.1.1 Comfort Profiling Overview

The purpose of the Personalised Comfort Profiling (PCP) engine is to analyse 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. The updated engine is specially designed to extract insight exclusively from timeseries data with no other sources of information required, constituting this way a purely data-driven solution. Furthermore, all separate user profiles must refer to regularly occupied spaces by the same users to guarantee homogeneity in user behaviour imprinted on preceding data. The approach considered for the comfort profiling concerns a seasonality-based analysis in order to compare data correlated to similar outdoor conditions. To enable the comparison between previous and current user behaviour, the comfort profiles need to be defined upon an extended period of time to address the alterations of the outdoor conditions and yield a reference comparable to the current measurements. To achieve this, preceding data of the previous year must be available for the algorithm training. During the validation period (M19-M36) other approaches will be considered as well, based on factors of the outdoor condition such the outdoor ambient temperature and solar irradiation.

The followed data-driven methodology coincides for both thermal and visual comfort with the exception of some modifications to tackle the high variability in illuminance measurements. The product of the comfort profiling analysis will be utilised for the calculation of comfort indicators, subject to the quality and completeness of the acquired datasets.

According to the system architecture [35], the calculation of the dynamic KPIs (Comfort, Energy performance and Cost & Economic) will be realized by the D^2EPC Calculation Engine. Regarding the comfort profile extraction, a separate PCP engine component (not part of the calculation engine) will take over the calculation of the user boundaries. The PCP engine comprises of three subcomponents which perform three separate procedures described below:

- **Data pre-processing**: This subcomponent is responsible for the retrieval of necessary building configuration and ambient sensing data (air temperature, illuminance and occupancy) which are further processed to be channelled as input to the algorithm training subcomponent
- **Algorithm training**: This subcomponent comprises of the machine learning algorithms which are trained based on the processed historical datasets
- **Profile extraction**: This subcomponent delivers as output the extracted profiles

5.1.2 The SAX Algorithm

D^2EPC's profiling engine steps on the solution provided by Hypertech which has been updated with a state-of-the-art clustering algorithm that realises the profile extraction solely on historic timeseries data. The Symbolic Aggregate approXimation is a relatively simple algorithm with low computational complexity. The algorithm provides a high-level representation of timeseries datasets by binning the continuous input into intervals. The sequence of floats is transformed to a sequence of symbols from the English Alphabet and each symbol corresponds to a specific range. Through this dimensionality reduction, the algorithm manages to confine the noise in data and capture the trend of the series without significant loss of information. In the context of D^2EPC, the SAX algorithm will be applied on (dry-bulb) temperature and illuminance datasets. Regarding the temperature, it has been proven to be suitable for symbolic approximation, as the algorithm succeeds to identify and cluster the variations and trends inside the training data. Meanwhile, SAX clustering on illuminance time series is unprecedented and will be introduced as innovation in the D^2EPC.

In Figure 4, an example of SAX algorithm implementation in temperature data is presented. Two inhomogeneous clusters have been formed, 'a' and 'b' corresponding to two different ranges. Complete documentation on the SAX algorithm can be find in [36] and [37]

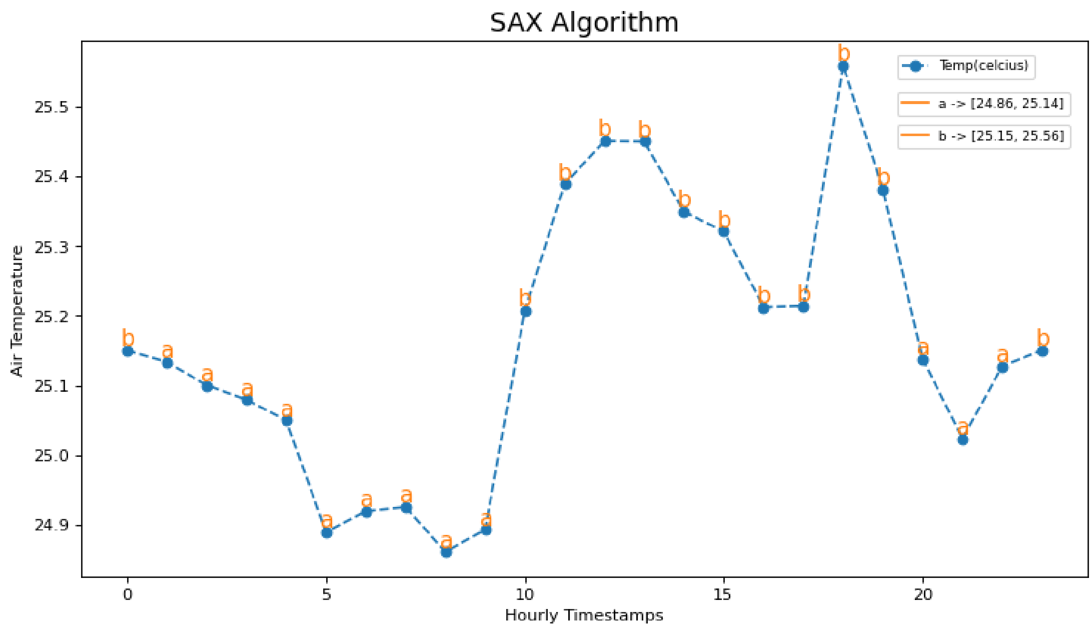

Figure 4. SAX algorithm with two clusters applied on a 24H temperature dataset

6 Conclusions

D2.2 is the first version of T2.2 deliverable which provides insights on the human-centric profiles that affect the building's performance in regards to the user's comfort and wellbeing. The user profiles are defined upon a set of dynamic comfort indicators which are calculated solely on IoT data acquired by the building. The dynamic nature of HC&W KPIs points to a data-driven approach which is materialised by specialised algorithms applied on the data streams to yield concrete results without further requirement of occupant's feedback.

Within D^2EPC, the occupant's comfort and wellbeing are examined in the context of three different indoor environmental quality pillars, i.e., the thermal and visual comfort as well as the quality of indoor air. To quantify the building's overall comfort performance, various environmental parameters are utilised, along with the respective boundaries of proper building operation per parameter. A hybrid approach is delivered within D2.2 to determine the acceptable ranges. The approach steps on the personalised comfort profiling engine which contains a machine-learning clustering algorithm able to identify patterns and trends on preceding user data in order to infer the occupant's preferred limits. In cases when the PCP utilisation is not considered applicable or relevant, building code boundaries obtained by the literature are implemented. After the boundary determination, the KPIs are calculated based on methodologies recommended by European and national standards to evaluate the building's performance in a clearly-defined manner.

The thermal comfort assessment is based on well-defined and measurable metrics corresponding to the air temperature and relative humidity supplemented by two thermo-physiological parameters which examine the combined influence of temperature and humidity in residential and commercial premises. The visual comfort is assessed through the illuminance of a space, either adjusted to the occupant's preferences in residences or adhering to predefined levels proposed by the literature. Regarding the I.A.Q., the assessment is based on a set of air quality metrics (such as CO2, VOCs and PMs) obtained by the Level(s) framework that affect the human respiratory system in poorly ventilated spaces.

The next version of the deliverable is expected after a wide demonstration period during which the HC&W KPIs will be tested on real pilot data. These tests will contribute to the validation and fine-tuning of the KPIs as well as the calibration of the PCP engine. All modification will be documented in detail in the next version of the report towards delivering the finalised version of the comfort and wellbeing indicators framework.

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ANNEX A: Thermal Comfort Indicators

Indicator Name	Indicator Description	Units	Static/Dynamic	Category	Calculation Procedure	Input Data				Type of the building	Comments
						Metric	Unit	Spatial Granularity	Temporal Granularity		
Deviation from the temperature range	Calculate the number or % of hours (during which the building is occupied) when the temperature is outside a specified range from the personalized comfort boundaries (EN 15251)	%	Dynamic	Thermal Comfort	**Total Hours of building occupation in the period of interest:** $\sum_{i=t_0}^{t_n} 1$ **Hours out of range:** $\sum_{i=t_0}^{t_n} 1, \; [\text{if } T_{upper} - \overline{T_i} < 0 \text{ or } \overline{T_i} - T_{bottom} < 0]$ **Frequency of Deviation:** (Hours out of range / Total Hours) *100	Indoor hourly mean Temperature: $\overline{T_i}$	°C	Room level	1 hour	Residential/Commercial	The personalised comfort boundaries are extracted from the comfort profiling engine. If that's not feasible, building code boundaries found from literature, are utilised
						Upper Temp Limit: T_{upper}	°C	Room level	1 hour		
						Bottom Temp Limit: T_{bottom}	°C	Room level	1 hour		
						First timestamp: t_0	datetime	Room level	1 hour		
						Last timestamp: t_n	datetime	Room level	1 hour		
						Occupancy Status	Binary	Room level	1 hour		
Thermal Degree Hours	The time during which the actual temperature exceeds the personalized range (occupied hours) is weighted by a factor which is a function depending on by how many degrees, the range has been exceeded (EN 15251	Numeric	Dynamic	Thermal Comfort	**Weighting factor:** $W_f = \lvert \overline{T_i} - T_{limit} \rvert$ **Hours out of range (Warm period):** $\sum_{i=t_0}^{t_n} W_{fw}, \; [\text{if } T_{upper} - \overline{T_i} < 0]$ **Hours out of range (Cold period):** $\sum_{i=t_0}^{t_n} W_{fc}, \; [\text{if } \overline{T_i} - T_{bottom} < 0]$	Indoor hourly mean Temperature: $\overline{T_i}$	°C	Room level	1 hour	Residential/Commercial	The personalised comfort boundaries are extracted from the comfort profiling engine. If that's not feasible, building code boundaries found from literature, are utilised
						Upper Temp Limit: T_{upper}	°C	Room level	1 hour		
						Bottom Temp Limit: T_{bottom}	°C	Room level	1 hour		
						First timestamp: t_0	datetime	Room level	1 hour		
						Last timestamp: t_n	datetime	Room level	1 hour		
						Occupancy Status	Binary	Room level	1 hour		
Deviation from the humidity range	Calculates the number or % of hours (during which the building is occupied) when the relative humidity is outside a specified range (EN 15251)	%	Dynamic	Thermal Comfort / Indoor air quality	**Total Hours of building occupation in the period of interest:** $\sum_{i=t_0}^{t_n} 1$ **Hours out of range:** $\sum_{i=t_0}^{t_n} 1 \; [\text{if } RH_{upper} - \overline{RH} < 0 \text{ or } \overline{RH} - RH_{bottom} < 0]$ **Frequency of Deviation:** (Hours out of range / Total Hours) *100	Indoor hourly mean relative Humidity: $\overline{RH}$	%	Room level	1 hour	Residential/Commercial	The building code boundaries according to Level(s) correspond to [40-60%])
						Upper relative Humidity Limit: RH_{upper}	%	N/A	N/A		
						Bottom relative Humidity Limit: RH_{bottom}	%	N/A	N/A		
						First timestamp: t_0	datetime	Room level	1 hour		
						Last timestamp: t_n	datetime	Room level	1 hour		
						Occupancy Status	Binary	Room level	1 hour		

Deviation from the acceptable WBGT levels	Calculate the % of hours (during which the building is occupied) when the thermophysiological parameter 'Wet-Bulb Global Temperature' (as defined in ISO 7243:2017) is greater than a specified value based on the workload	%	Dynamic	Thermal Comfort	**Calculate T_{wb} based on T_{db} and RH:** $T_w = T \operatorname{atan}[0.151977(RH\% + 8.313659)^{1/2}] + \operatorname{atan}(T + RH\%) - \operatorname{atan}($ $+ 0.00391838(RH\%)^{3/2} \operatorname{atan}(0.023101 RH\%) - 4.686035.$ **Calculate WGBT based on T_{db} and T_{wb}:** $WGBT = 0.7 * T_{db} + 0.3 * T_{wb}$ **Total Hours of building occupation in the period of interest (cooling):** $\sum_{i=t_0}^{t_n} 1$ **Hours out of range of the proposed WBGT taking into account the workload of the space:** $\sum_{i=t_0}^{t_n} 1, \; [\text{if WBGT} > \text{threshold}]$ **Frequency of Deviation:** (Hours out of range / Total Hours) *100	Indoor hourly air dry-bulb temperature **T_{db}**	ºC	Room level	1 hour	Commercial	Based on the metabolic rate of several work catergories along with the percentage of work effort, specific levels are generated tailored to each building's usage. The wet bulb temperature is estimated based on the dry bulb temperature and the relative humidity. The WBGT is calculated for the cooling period
						Indoor hourly relative temperature **RH**	%	Room level	1 hour		
						WBGT threshold	constant	Room level	1 hour		
						First timestamp: **t_0**	datetime	Room level	1 hour		
						Last timestamp: **t_n**	datetime	Room level	1 hour		
						Occupancy Status	Binary	Room level	1 hour		
Humidex levels	The Humidex is physiological parameter (defined in ISO 7243:2017). The indicator is reported based on the % of hours of each level compared to the total hours of the period of interest	% per level	Dynamic	Thermal Comfort	**Calculate T_{dew} based on T_{db} and RH:** $L = \ln\left(\frac{RH}{100}\right)$ $M = 17.27 * T_{db}$ $N = 237.3 + T_{db}$ B = (L+(M+N))/17.27 $T_{dew} = (237.3 * B)/(1 - B)$ **Calculate Humidex based on T_{db} and T_{dew}:** $H = T_{db}\frac{5}{9}\left[6.11 \times e^{5417.7530(\frac{1}{273.16} - \frac{1}{273.15+T_{dew}})} - 10\right]$ **Total Hours of building occupation in the period of interest:** $\sum_{i=t_0}^{t_n} 1$ **Total Hours corresponding to each level for the period of interest:** $Hours\ per\ level: \sum_{i=t_0}^{t_n} 1, \; [If\ H_{bot,level} \leq H \leq H_{up,level}]$ **Level proportion:** (Hours per level / Total Hours) *100 **Humidex levels** Leve I: 20 to 29 -> Little to no discomfort Leve II: 30 to 39 -> Some discomfort Leve III: 40 to 45 -> Great discomfort Leve VI: Above 45 -> Dangerous	Indoor hourly air dry-bulb temperature **T_{db}**	ºC	Room level	1 hour	Residential/Commercial	The Humidex index is calculated separately for the cooling and heating period
						Indoor hourly relative Humidity: **RH**	%	Room level	1 hour		
						Hourly Humidex: **H**	constant	Room level	1 hour		
						Humidex level's bottom limit: $\boldsymbol{H_{bot,level}}$	constant	N/A	N/A		
						Humidex level's upper limit: $\boldsymbol{H_{up,level}}$	constant	N/A	N/A		
						First timestamp: **t_0**	datetime	Room level	1 hour		
						Last timestamp: **t_n**	datetime	Room level	1 hour		
						Occupancy Status	Binary	Room level	1 hour		

ANNEX B: Visual Comfort Indicators

Indicator Name	Indicator Description	Units	Static/Dynamic	Category	Calculation Procedure	Input Data				Type of the building	Comments
						Metric	Unit	Spatial Granularity	Temporal Granularity		
Deviation from the set Illuminance boundary	Summation of all the daylight hours of a regularly occupied space during which the illuminance was lower than the profiling engine bottom boundary, compared to the total hours of the period of interest	%	Dynamic	Visual Comfort	**Total Daylight Hours of building occupation in the period of interest :** $\sum_{i=t_0}^{t_n} 1$ **Hours under the bottom boundary:** $\sum_{i=t_0}^{t_n} 1\ ,\ [if\ \overline{Ev_i} - Ev_{set} < 0]$ **Frequency of deviation:** (Hours out of Range / Total Hours) *100	Indoor hourly mean Illuminance: $\overline{Ev_i}$	Lux	Room level	1 hour	Residential/Commercial	The bottom set illuminance boundary is determined by the personalised comfort profiling engine, applied in the visual comfort. Only the bottom limit is examined, assuming
						Bottom set Illuminance Limit: Ev_{set}	Lux	Room level	1 hour		
						First daylight timestamp: t_0	datetime	Room level	1 hour		
						Last daylight timestamp: t_n	datetime	Room level	1 hour		
						Occupancy Status	Binary	Room level	1 hour		
Deviation from the standard Illuminance levels	Summation of all the daylight hours of a regularly occupied space during which the illuminance was lower than the acceptable levels determined within EN 12464, compared to the total hours of the period of interest	%	Dynamic	Visual Comfort	**Total Daylight Hours of building occupation in the period of interest :** $\sum_{i=t_0}^{t_n} 1$ **Hours under the bottom boundary:** $\sum_{i=t_0}^{t_n} 1\ ,\ [if\ \overline{Ev_i} - Ev_{code} < 0]$ **Frequency of deviation:** (Hours out of Range / Total Hours) *100	Indoor hourly mean Illuminance: $\overline{Ev_i}$	Lux	Room level	1 hour	Commercial	The illuminance levels obtained from the literature are separately examined as they have been proposed (EN 12464) for different types of spaces (and activities). The preferred illuminance levels of an occupant do not always coincide with the optimal ones.
						Building code Illuminance level: Ev_{code}	Lux	N/A	N/A		
						First daylight timestamp: t_0	datetime	Room level	1 hour		
						Last daylight timestamp: t_n	datetime	Room level	1 hour		
						Occupancy Status	Binary	Room level	1 hour		
Set Visual Degree Days	The daylight hours during which the space is occupied and the measured illuminance remains below the profiling engine bottom boundary. The calculation is weighted by a factor which is a function depending on by how many degrees the	Numeric	Dynamic	Visual Comfort	**Weighting factor:** $W_f = \lvert\overline{Ev_i} - Ev_{set}\rvert$ **Visual degree days:** $\sum_{i=t_0}^{t_n} W_f,\ [\text{if } Ev_{set} - \overline{Ev_i} > 0]$	Indoor hourly mean Illuminance: $\overline{Ev_i}$	Lux	Room level	1 hour	Residential/Commercial	The set visual degree hours quantify the deviation of the measured illuminance from the minimum acceptable illuminance as determined from the visual comfort profiling engine. They take into account not only the number of hours below the limit but also the magnitude of the difference between measured and acceptable illuminance
						Bottom Set Illuminance Limit: Ev_{set}	Lux	Room level	1 hour		
						First daylight timestamp: t_0	datetime	Room level	1 hour		

	average hourly illuminance was below The bottom boundary (EN 15251)					Last daylight timestamp: t_n	datetime	Room level	1 hour		
						Occupancy Status	Binary	Room level	1 hour		
Standard Visual Degree Days	The daylight hours during which the space is occupied and the measured illuminance remains below the building code level provided within EN 12464. The calculation is weighted by a factor which is a function depending on by how many degrees the average hourly illuminance was below the acceptable level	Numeric	Dynamic	Visual Comfort	**Weighting factor:** $W_f = \lvert\overline{Ev_i} - Ev_{code}\rvert$ **Visual degree days:** $\sum_{i=t_0}^{t_n} W_f, [\text{if } Ev_{code} - \overline{\overline{Ev_i}} > 0]$	Indoor hourly mean Illuminance: $\overline{Ev_i}$	Lux	Room level	1 hour	Residential/Commercial	The standard visual degree hours quantify the deviation of the measured illuminance from the minimum acceptable illuminance level as determined in EN 12464 for different spaces (and activities). They take into account not only the number of hours below the limit but also the magnitude of the difference between measured and acceptable illuminance
						Building code Illuminance level: Ev_{code}	Lux	Room level	1 hour		
						First daylight timestamp: t_0	datetime	Room level	1 hour		
						Last daylight timestamp: t_n	datetime	Room level	1 hour		
						Occupancy Status	Binary	Room level	1 hour		

ANNEX C: Indoor Air Quality Indicators

C.1 Main I.A.Q. indicators

Indicator Name	Indicator Description	Units	Static/Dynamic	Category	Calculation Procedure	Input Data				Type of Building	Comments
						Metrics	Units	Spatial Granularity	Temporal granularity		
CO_2 indoors	The CO2 concentration of a space along with the respective outdoor concentration are measured for a period of interest (occupied hours). CEN/TR 16798 defines four distinct categories for the diffrerences between indoor/outdoor CO2 concentrations. The indicator is reported based on the % of hours of each category compared to the total hours of the period of interest	% per category	Dynamic	IAQ	**Calculate the differences between indoor/outdoor CO2 concentrations:** $CO_2 = CO_{2,indoors} - CO_{2,outdoors}$ **Total Hours of building occupation in the period of interest:** $\sum_{i=t_0}^{t_n} 1$ **Total Hours corresponding to each category for the period of interest:** $Hours\ per\ category\colon \sum_{i=t_0}^{t_n} 1,\ [If\ CO \leq CO_{2cat}\ ]$ **Category proportion:** (Hours per category / Total Hours) *100 **Categories according to CEN/TR 16798-1/2:2019**: I category – 500 ppm when the air flow rate is 10 l/s II category – 800 ppm when the air flow rate is 7 l/s III category – 1350 ppm when the air flow is 4 l/s IV category – 1550 ppm when the air flow is 4 l/s	Hourly outdoor CO_2 concentration : $\boldsymbol{CO_{2,outdoors}}$	ppm	Room level (Intake air duct, outdoor sensor, or the nearest measuring station)	1 hour	Residential/Commercial	The mentioned limits of CO_2 concentrations correspond to the deviation from outdoor air CO_2 concentration. It is further assumed standard CO_2 emission of a person 20L/(h/person). As mentioned in the Ventilation rate indicator, due to the challenges of its estimation, CO_2 levels will be examined irrespective to ventilation rate or air flow rates
						Hourly indoor CO2 concentration : $\boldsymbol{CO_{2,indoors}}$	ppm	Room level (Extract air duct or CO2 sensor mounted at least 1,5m above the floor)	1 hour		
						C02 category: $\boldsymbol{CO_{2cat}}$	ppm	N/A	N/A		
						First timestamp: t_0	Datetime	Room level	1 hour		
						Last timestamp: t_n	Datetime	Room level	1 hour		
						Occupancy Status	Binary	Room level	1 hour		
Total Total Volatile Organic Compounds (TVOCs)	TVOC is the sum of the concentrations of the identified and unidentified volatile organic compounds in the indoor air.	Numeric	Dynamic	IAQ	**Average TVOC** The TVOC measurements are reported on a 28-day basis. If data of smaller granularity are provided, the values are averaged per 28-day intervals. **Limits** According to EN 16798-1, 2019: <1000 μg/m³ (low emitting building) <300 μg/m³ (very low emitting building)	TVOC measurement	μg/m³	Room level (at supply air duct ideally)	28 days	Residential/Commercial	
Particulate matter <2,5 μm (PM 2.5)	Particles' that are 2,5 μm in diameter or smaller concentration in the indoor air. According to EN 16890-1, particulate matter which	Numeric	Dynamic	IAQ	**Average PM 2.5** The PM measurements when the space is occupied are grouped and averaged by day and then all days within the period of interest are averaged to produce a single value. The calculated value is compared with the per-24h limit. Alternatively,	PM2.5 measurement	μg/m³	Room level (at extract air duct ideally)	1 hour	Residential/Commercial	

	passes through a size-selective inlet with a 50% efficiency cut-off at 2.5μm aerodynamic diameter.				the same measurements are averaged on yearly basis and the calculated value is compared to the per-1year limit **Limits** According to EN 16798-1: <25 μg/m3 (per 24 h) 10 μg/m3 (per year)	Occupancy status	binary	Room level	1 hour		
						Occupancy status	binary	Room level	1 hour		

C.2 Complementary I.A.Q. indicators

Indicator Name	Indicator Description	Units	Static/Dynamic	Category	Calculation Procedure	Input Data				Type of Building	Comments
						Metrics	Units	Spatial Granularity	Temporal granularity		
Ventilation rate (air flow)	The ventilation rate is the magnitude of outdoor air flow to a room or building through the ventilation system or device. The indicator is reported based on the % of hours of each category compared to the total hours of the period of interest	% per category	Dynamic	IAQ	**Average ventilation rate** Rough estimation (naturally ventilated buildings) of air change rate with hourly CO_2 concentrations on the single zone approximation when no sources are present: $A = (\ln(CO2_{t_0}) - \ln(CO2_{t_n}))/(t_n - t_0)$	Carbon Dioxide conentration measured at two different timestamps: $CO2_t$	ppm	Room level (at supply air duct ideally)	1 hour	Residential/Commercial	The ventilation rate can be estimated on a daily basis at specific timestamps and then averaged for the period of interest. The estimation of ventilation rate is a challenging task due to several assumptions made (e.g., no other CO_2 sources other than occupants). It is further influenced by many factors (# of occupants, open/close windows etc.) which may generate even worse results. Based on the results it may be deemed out of scope. In mechanically ventilated buildings actual ventilation rates may be acquired by sensors of the ventilation system. It is generally recommended to measure ventilation rates at building scale
					The first and second CO_2 measurements must correspond to occupied and unoccupied hours respectively.	First timestamp: t_0	datetime	Room level	1 hour		
					After conversion the ventilation rate in l/s/m²: $Vr = \frac{A \times Vol \times 1000}{3600}/S$	Last timestamp: t_n	datetime	Room level	1 hour		
					Total Hours of building occupation in the period of interest: $\sum_{i=t_0}^{t_n} 1$	Room surface: S	m²	Room level	N/A		
					Total Hours corresponding to each category for the period of interest: $Hours\ per\ category: \sum_{i=t_0}^{t_n} 1,\ [If\ Vr \leq Vr_{cat}\ ]$ **Category proportion:** (Hours per category / Total Hours) *100	Room volume: Vol	m³	Room level	N/A		
					Ventilation rate limits (for diluting all emissions from building) According to CEN/TR 16798-1:2019:	Ventilation category: Vr_{cat}	l/s/m²	N/A	N/A		

					I category – 2 l/(s*m^2) II category – 1,4 l/(s*m^2) III category – 0,8 l/(s*m^2) IV category – 0,55 l/(s*m^2)	Occupancy Status	Binary	Room level	1 hour		
Benzene	Benzene concentration in the indoor air.	Numeric	Dynamic	IAQ	**Average Benzene** The Benzene measurements are reported on a 28-day basis. If data of smaller granularity are provided, the values are averaged per 28 days intervals. **Limits** According to EN 16798-1: 3.25 $\mu g/m3$	Benzene measurement	$\mu g/m^3$	Room level (at supply air duct ideally)	28 days	Residential/Commercial	
Formaldehyde	Formaldehyde concentration in the indoor air.	Numeric	Dynamic	IAQ	**Average Formaldehyde** The Formaldehyde measurements are reported on a 28-day basis. If data of smaller granularity are provided, the values are averaged per 28-day intervals **Limits** According to EN 16798-1 <100 $\mu g/m^3$ (low emitting building) <30 $\mu g/m^3$ (very low emitting building)	Formaldehyde measurement	$\mu g/m^3$	Room level (at extract air duct ideally)	28 days	Residential/Commercial	
Radon	Radon concentration in the indoor air.	Numeric	Dynamic	IAQ	**Average Radon** The Radon measurements are reported on a 28-day basis. If data of smaller granularity are provided, the values are averaged per 28-day intervals 100 Bq/m^3 (based on WHO)	Radon measurement	Bq/m^3	Room level (at extract air duct ideally)	28 days	Residential/Commercial	
Particulate matter <10 µm (PM 10)	Particles' that are 10 µm in diameter or smaller concentration in the indoor air. According to EN 16890-1, particulate matter which passes through a size-selective inlet with a 50% efficiency cut-off at 10 aerodynamic diameter.	Numeric	Dynamic	IAQ	**Average PM 10** The PM measurements when the space is occupied are grouped and averaged by day and then all days within the period of interest are averaged to produce a single value. The calculated value is compared with the per-24h limit. Alternatively, the same measurements are averaged on yearly basis and the calculated value is compared to the per-1year limit **Limits** According to EN 16798-1: <50 $\mu g/m^3$ (per 24 h) <20 $\mu g/m^3$ (per year)	PM2.5 measurement	$\mu g/m^3$	Room level (at extract air duct ideally)	1 hour	Residential/Commercial	
						Occupancy status	binary	Room level	1 hour		