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Introductory Human-Centric Exposure Modelling (H-CEM) method for estimating exposure to indoor air PM2,5

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Foreword

This CEN Workshop Agreement (CWA 18407:2026) has been developed in accordance with the CEN-CENELEC Guide 29 “CEN/CENELEC Workshop Agreements – A rapid way to standardization” and with the relevant provisions of CEN/CENELEC Internal Regulations - Part 2. It was approved by the Workshop [CEN/WS TWINAIR, the secretariat of which is held by UNE] consisting of representatives of interested parties on 2026-06-22, the constitution of which was supported by CEN following the public call for participation made on 2025-10-06. However, this CEN Workshop Agreement does not necessarily include all relevant stakeholders.

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Introduction

Origin and Properties in indoor environments:

Airborne particles are solid or liquid particles suspended in the atmosphere. Particles with an aerodynamic diameter less or equal to 2,5 µm (PM2,5) can remain suspended in the atmosphere during longer periods. They can also be readily transported through indoor airflow affecting human health climate and ecosystems.

PM2,5 are emitted from a wide variety of sources; from a combination of primary and secondary sources, arising both indoor and outdoor environments. Moreover, PM2,5 composition can vary significantly depending on its source, chemical formation processes, and transport routes. Elevated PM2,5 levels can also be found indoors, containing organic aerosols from cooking activities, combustion by-products from heating devices, fireplaces, wood stoves, candles, or smoking, as well as resuspended biological and mineral material from surfaces and various human activities. Outdoor generated PM2,5 may contain secondary inorganic aerosols, traffic-related particles, or industrial emissions. As a result, their physicochemical properties and potential health impacts of can differ significantly across environments.

Primary PM2,5 consists of particles emitted directly into the atmosphere. Indoor primary sources vary by building type and may include:

- Residential environments: cooking activities; combustion from candles, fireplaces, or wood stoves; smoking; resuspension from carpets and surfaces;

- Educational environments: chalk dust; high occupant activity; cleaning procedures;

- Healthcare environments: aerosol-generating medical procedures; frequent cleaning and disinfection; movement of staff and equipment;

- Office environments: emissions from printers and copiers; HVAC-related dust release; occupant-related resuspension.

Outdoor PM2,5 can penetrate indoors through mechanical and natural ventilation, open windows and doors, and leak through the building envelope. Thus, indoor PM2,5 levels depend strongly on building characteristics—including ventilation rate and type, filtration efficiency, airflow distribution, room geometry and occupant behaviour (window opening, activity level, and use of combustion appliances). Consequently, indoor PM2,5 concentrations can exhibit significant temporal fluctuations.

Providing better insights on the contributions of indoor-generated and outdoor-origin PM2,5 is crucial for accurate exposure assessment. This knowledge supports the Human-Centric Exposure Modelling (H-CEM) method and the complementary estimation of the Infiltration Factor (F_{inf}), which quantifies the portion of outdoor particles on indoor air quality.

Health implications of PM2,5 in indoor environments

PM2,5 is associated with a wide range of adverse health impacts due to its ability to enter the human body through nasal passages, reach the lungs and penetrate systemic circulation. Among the health impacts, aggravated asthma, reduced lung function, increased hospital admissions, cardiovascular stress, and premature deaths have been reported in the literature during the last decades.

The World Health Organization (WHO) has identified PM2,5 as the major pollutant provoking public-health issues. Consequently, specific limits have been for the protection of human health:

- Annual mean PM2,5: 5 µg m^{-3}

- 24-hour mean PM2,5**:** 15 µg m^{-3}

It should be noted that no threshold has been identified below which PM2,5 is considered harmless.

Additionally, the European Union has also set PM2,5 limits under the Ambient Air Quality Directives (2008/50/EC):

- Annual limit value: 25 µg m^{-3}

Ongoing updates to EU air-quality legislation are expected to introduce stricter annual limit values that more closely align with WHO guideline levels.

Although these values apply to ambient air quality, they are directly relevant to indoor exposure assessments since people spend most of their time indoors and because indoor environments contain both indoor-generated PM2,5 and outdoor infiltrated PM2,5. Thus, indoor PM2,5 exposure often constitutes the dominant portion of total personal exposure.

These health considerations reinforce the need for harmonized approaches such as the Human-Centric Exposure Modelling (H-CEM) method and supporting methodologies that quantify the outdoor contribution to indoor particulate concentrations, enabling more accurate assessment of inhaled doses across different indoor environments. Including different human breathing patterns in order to evaluate the daily inhalation burden and its implications for human health.

1 Scope

This document specifies a Human-Centric Exposure Modelling (H-CEM) approach to estimate human exposure in occupied indoor environments. The H-CEM method integrates information on indoor particle concentrations, environmental and airflow conditions, and human physiological characteristics to assess inhaled particulate matter under realistic conditions.

Standardized reference measurement of PM2,5 mass concentration is defined in ISO 16000-37. General sampling strategy principles for indoor air are defined in ISO 16000-1. The present CWA complements these standards and does not replace reference sampling or laboratory-based measurement methods defined in the ISO 16000 series. Where regulatory or compliance measurements are required, relevant ISO 16000 standards apply.

To support the accurate application of the H-CEM method, this document also includes a complementary methodology for quantifying the relationship between indoor and outdoor PM2,5 concentrations. This supporting methodology uses simultaneous, high temporal-resolution measurements obtained from low-cost particle sensors (LCSs), together with statistical analysis for quality control (QC) procedures assurance, to estimate the infiltration factor (F_{inf}) and to distinguish between outdoor-origin and indoor-generated particulate matter. The resulting parameters provide essential input data that enhance the reliability and representativeness of H-CEM exposure estimations.

The guidelines presented in this document cover the installation and deployment of low-cost sensors, the sampling methodology, and the data-processing procedures required to obtain valid particle concentration measurements for exposure modelling. These procedures are designed to address practical challenges associated with assessing human exposure in indoor environments, where individuals spend the majority of their time, more than 90 %, and where particle levels may show significant spatial and temporal fluctuations.

This document is applicable to a wide range of indoor environments; residential, educational, offices, and other occupied indoor environments where the objective is to characterize PM2,5 exposure under typical occupancy and ventilation conditions.

This document does not specify procedures for:

- regulatory compliance assessment of indoor or outdoor air quality;
- real-time indoor air quality control or operational monitoring;
- source apportionment of emissions arising exclusively from indoor activities such as cooking or smoking;
- characterization of pollutants outside the PM2,5 size fraction.

The guidelines are intended for researchers, practitioners, digital-twin developers, building engineers, and exposure modelers requiring a harmonized framework for conducting indoor particulate exposure investigations and for applying the Human-Centric Exposure Modelling (H-CEM) method.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 16000-1, *Indoor air — Part 1: General aspects of sampling strategy*

ISO 16000-34, *Indoor air — Part 34: Strategies for the measurement of airborne particles*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at http://www.iso.org/obp/

— IEC Electropedia: available at http://www.electropedia.org/

3.1
human bubble domain
three-dimensional CFD subdomain surrounding the human body, typically with a radius between 0,7 m and 1,2 m, representing the near-field environment where thermal plumes, respiration, and local airflow influence pollutant transport and inhalation

3.2
personal exposure
time-averaged or time-integrated flux of particulate matter entering the respiratory tract, calculated from local PM2,5 concentration fields and inhalation flow rates

3.3
active interaction radius
characteristic distance around the human body within which human-induced airflow measurably affects particle trajectories and concentration gradients

3.4
physiological boundary conditions
time-dependent inflow and outflow boundary conditions applied at the mouth or nostrils representing inhalation and exhalation cycles, breathing rates, flow rates, and temperature

3.5
local thermal plume
buoyancy-driven upward airflow generated by human body heat that affects local dispersion and transport of airborne particles

4 Infiltration Factor (F_{inf}) estimation

4.1 General

This clause specifies the methodology for estimating the infiltration factor (F_{inf}), which quantifies the fraction of outdoor PM2,5 that penetrates indoors under infiltration-dominated conditions. General aspects of indoor air sampling strategy shall be in accordance with ISO 16000-1.

Standardized reference measurement of PM2,5 mass concentration is defined in ISO 16000-37. General sampling strategy principles for indoor air are defined in ISO 16000-1. The present CWA complements these standards and does not replace reference sampling or laboratory-based measurement methods defined in the ISO 16000 series. Where regulatory or compliance measurements are required, relevant ISO 16000 standards apply.

The subclauses below specify additional requirements specific to F_{inf} estimation using low-cost optical sensors (LCSs) that will supplement the Human-Centric Exposure Modelling (H-CEM) methodology, which are not covered by the ISO 16000 series.

4.2 Monitoring objectives

The monitoring framework described in this clause is intended to:

- Characterize time-resolved indoor and outdoor PM2,5 mass concentrations under typical occupancy and ventilation conditions;
- Provide synchronized datasets suitable for indoor–outdoor comparison;
- Provide validated input data for the estimation of the F_{inf};
- Provide validated input data for H-CEM exposure calculations.

This document addresses only PM2,5 mass concentration and does not include measurement of particle number concentration (see ISO 16000-42) or chemical composition.

4.3 Deployment and positioning

4.3.1 General

Indoor and outdoor monitoring devices shall be deployed and positioned in accordance with ISO 16000-1 and ISO 16000-34. The following additional requirements apply specifically to F_{inf} estimation.

4.3.2 Pre-deployment collocation check

Before deployment, all monitoring devices intended for collocated and simultaneous indoor–outdoor measurements shall be collocated and operated side by side for a minimum period of one week.

The collocation check shall be performed before field deployment in order to assess the comparability of device responses under the same environmental conditions. Indoor and outdoor devices shall be time-synchronized before the collocation period starts. The results of the collocation check, including the measurement period, device identifiers, data completeness, observed agreement between devices, and any device exclusions or correction factors, shall be documented. Whenever possible, additional monitors with certified performance should be included in the pre-deployment collocation check.

The collocation check shall be performed in an environment where PM2,5 concentrations exhibit sufficient temporal variability to allow comparison of device response. Periods with negligible concentration variability, such as closed chambers or inactive spaces with persistently low and flat PM2,5 levels, shall not be used as the sole basis for assessing sensor agreement.

Where possible, the collocation dataset should include periods with meaningful PM2,5 variation, for example concentration changes of approximately ±20 $\mu g\ m^{-3}$ or other documented variation appropriate to the intended monitoring environment.

4.3.3 Deployment requirements

- Indoor devices shall be positioned at approximately 1,5 m height, representative of the occupant breathing zone (ISO 16000-1, ISO 16000-34).
- Sensors shall be placed away from known indoor particle sources and ventilation outlets (ISO 16000-34).
- The paired outdoor device shall be located on the same building façade as the indoor sensor.
- All devices shall be time-synchronized to within ±2 minutes prior to deployment.

- PM2,5 device orientation and placement should be in accordance with manufacturer specifications and never facing upwards to avoid PM gravimetric deposition.

- All placement decisions shall be documented to ensure reproducibility of modelling results (ISO 16000-1).

4.4 Data quality control and pretreatment

General data quality requirements shall be in accordance with ISO 16000-1 and ISO 16000-34. The following additional requirements apply specifically to LCS-based F_{inf} estimation:

- The first 24 hours of data after deployment shall be excluded to allow sensor stabilization.

- Dual-channel agreement shall be monitored continuously as the primary LCS validation criterion; data from periods of significant channel disagreement shall be excluded.

- Indoor and outdoor datasets shall be temporally synchronized before analysis; periods without full overlap shall be excluded.

- Each analysis window shall contain a minimum of 75 % valid synchronized data points.

- Outlier detection and removal shall follow the procedure specified in Annex A.

- Flat data detection and removal shall follow a rolling window procedure, specified in Annex A.

- Indoor-source–dominated periods shall be identified and excluded using the MAD-based procedure specified in Annex A, retaining only infiltration-dominated data for F_{inf} estimation.

- All QC steps, exclusion criteria, and removed data periods shall be documented (ISO 16000-1).

4.5 Infiltration factor estimation methodology

4.5.1 General principle

The methodology for F_{inf} estimation is based on Bi et al. (2021), with modifications introduced in the TwinAIR project for seasonal segmentation and long-term LCS deployment. The detailed computational procedure is specified in Annex A.

F_{inf} is defined as the fraction of outdoor PM2,5 that penetrates indoors and remains suspended under infiltration-dominated conditions. It is estimated as the slope of a constrained linear regression between synchronized indoor and outdoor PM2,5 concentrations:

$$C_{\text{in(t)}} = F_{\text{inf}} \cdot C_{\text{out(t)}} + \varepsilon(\text{t})$$

where ε(t) represents residual variability due to deposition, ventilation fluctuations, and sensor noise. The regression is performed only on infiltration-dominated periods, identified and validated in accordance with Annex A.

4.5.2 Indoor-source event removal

Indoor-source–dominated periods are identified and excluded prior to F_{inf} estimation. The detection procedure shall follow the I/O ratio and LOWESS-based method specified in Annex A.

4.5.3 Infiltration factor estimation

F_{inf} is estimated from the cleaned infiltration-dominated dataset using the Moving-Block Bootstrap (MBB) procedure specified in Annex A. The following are reported:

- The mean F_{inf} value derived from the bootstrap distribution;
- The standard deviation of the bootstrap distribution as the uncertainty measure.

4.5.4 Seasonal segmentation

Where long-term datasets are available, F_{inf} should be estimated separately for distinct climatic periods (e.g. cold, warm, transitional seasons) to account for seasonal variability in building envelope performance, window-opening behaviour, and HVAC operation. Seasonal estimates may be aggregated to derive an annual F_{inf} characterization for use in H-CEM modelling.

5 Human-Centric Exposure Modelling (H-CEM)

5.1 General

This clause specifies the Human-Centric Exposure Modelling (H-CEM) framework for estimating human exposure to indoor PM2,5. The H-CEM approach combines indoor airflow and pollutant transport simulations with human physiological and behavioural parameters to quantify inhalation exposure under realistic indoor conditions.

5.2 Sequential H-CEM Methodology

5.2.1 Environmental characterization

The indoor environment shall be explicitly defined based on architectural and ventilation characteristics of the studied space. The computational domain shall include the full three-dimensional geometry of the indoor space, including walls, floor, ceiling, doors, windows, ventilation inlets, and exhaust outlets. All solid boundaries shall be assigned appropriate thermal and aerodynamic boundary conditions.

Ventilation systems shall be characterized by their airflow rates, supply air temperature, diffuser type, and exhaust locations. For mechanically ventilated spaces, inlet velocity profiles and turbulence quantities shall be specified based on measured data or design specifications. For naturally ventilated environments, window or opening pressure boundary conditions shall be applied.

Ambient environmental parameters shall include:

- PM2,5 background concentration (μg/m^3), either measured experimentally or obtained from literature values representative of the indoor environment;
- Air temperature (T), specified as a uniform value or spatially varying field depending on the thermal conditions;
- Relative humidity (RH), which may influence particle hygroscopic growth and deposition behaviour;
- Airflow regime, characterized by Reynolds number and turbulence intensity;
- Emission sources within the environment shall be explicitly defined. Each source shall be characterized by:
    - Emission rate (mg/s or particles/s);

- Particle size distribution (e.g., log-normal with specified geometric mean diameter);
- Temporal behaviour (continuous, intermittent, or transient);
- Source location and release height.

These parameters collectively define the baseline environmental conditions for subsequent transport and exposure calculations.

5.2.2 Human representation and breathing pattern profiling

Occupants shall be represented using a computational anthropomorphic model that approximates the geometry of the human body, including head, torso, and limbs. The model shall be positioned realistically within the indoor space, accounting for posture (standing or seated) and orientation relative to airflow and emission sources.

Physiological breathing parameters shall be prescribed to represent realistic human respiration. These parameters include:

- Breathing frequency (f_b) (breaths/min);
- Tidal volume (V_t) (L/breath);
- Minute ventilation ($\dot{V}_\mathrm{E}$) (L/min), defined as $\dot{V}_\mathrm{E} = f_\mathrm{b} \times V_\mathrm{t}$.

Breathing parameters shall be adjusted according to:

- Age group (child, adult, elderly);
- Gender, reflecting differences in lung volume and body size;
- Health state, including healthy individuals and those with respiratory conditions such as asthma.

Breathing shall be modelled as a time-dependent transient process, with inhalation and exhalation phases represented by periodic velocity or mass-flow boundary conditions at the nostrils or mouth. The inhalation–exhalation ratio and waveform (e.g., sinusoidal or piecewise linear) shall be selected based on physiological data.

To account for human thermal effects, a skin heat flux ranging from 50 to 100 W/m^2 shall be applied to the human surface. This heat release generates a buoyancy-driven thermal plume that significantly influences local airflow patterns and particle transport in the breathing zone.

5.2.3 Thermal transport

Thermal transport within the indoor environment shall be modelled using the energy conservation equation, coupled with the airflow field. Heat transfer mechanisms shall include convection, conduction, and buoyancy effects arising from temperature gradients.

Internal heat sources shall include, where applicable:

- Metabolic heat release from occupants;
- Heat generated by electrical equipment and lighting;
- Thermal contributions from ventilation air supply.

The human thermal plume shall be explicitly resolved to capture upward convective flows around the body, which strongly affects contaminant transport near the breathing zone. Wall and surface temperatures shall be specified or solved depending on the availability of thermal data.

Thermal stratification shall be considered in spaces where vertical temperature gradients are expected, such as rooms with displacement ventilation or limited air mixing. The Boussinesq approximation may be employed to account for buoyancy effects due to temperature differences.

5.2.4 Particle transport

PM2,5 transport shall be simulated using an Eulerian airflow field coupled with Lagrangian particle tracking, implemented as Lagrangian discrete phase model (DPM), in which individual particle trajectories are tracked through the computed airflow field. Particles shall be assumed spherical and characterized by their aerodynamic diameter and density.

Particle motion shall be governed by:

- Aerodynamic drag force;
- Gravitational settling;
- Buoyancy effects;
- Turbulent dispersion modelled using stochastic tracking.

Depositions on solid surfaces may be included through appropriate wall interaction models. Particle–particle interactions are neglected due to the dilute concentration regime.

Inhalation and exhalation processes shall be represented as transient boundary conditions at the breathing openings. During inhalation, particles entering the breathing zone may be captured and counted as inhaled mass. During exhalation, particles may be released back into the domain if exhaled aerosol is considered.

5.2.5 Exposure quantification

The instantaneous mass flux of PM2,5 entering the breathing zone shall be calculated by integrating the product of local particle concentration and airflow velocity over the inhalation area. Cumulative exposure shall be obtained by time integration of the inhaled mass flux.

Exposure assessment shall be performed by calculating the instantaneous inhaled mass flux of PM2,5 at the breathing interface. The inhaled mass flux shall be determined by integrating the product of local particle concentration and airflow velocity over the inhalation area (in n dA):

$$\dot{m}_{\mathrm{inh}}(t) = \int_A C_p(x,t)\ u(x,t)$$

where

C_{p} is the local particle mass concentration (µg m^{-3});

u is the local airflow velocity vector (m/s);

n is the unit vector normal to the inhalation surface (oriented inward toward the airway);

A is the inhalation cross-sectional area (m^2) at the mouth or nostril opening.

Cumulative exposure shall be obtained by time integration of the inhaled mass flux over the exposure duration:

$$m_{\mathrm{inh}} = \int_0^{\mathrm{T}} \dot{m}_{\mathrm{inh}}(t)\, dt$$

This approach allows direct comparison of exposure levels across different scenarios, breathing patterns, and health conditions. The methodology enables quantification of short-term peak exposure as well as long-term cumulative dose.

5.2.6 CFD validation and verification

The computational framework shall be verified and validated following established CFD best-practice guidelines to ensure numerical accuracy and physical reliability of the results. Verification shall include systematic grid-independence testing, time-step sensitivity analysis for transient simulations, and assessment of residual convergence and mass–energy conservation. Validation shall be conducted by comparison of simulated airflow, temperature, and PM2,5 concentration fields with experimental or benchmark data reported in the literature for indoor environments and breathing thermal plumes. Key validation metrics shall include velocity profiles in the breathing zone, temperature stratification, and particle concentration decay rates. Turbulence and particle models shall be selected based on prior validation in similar indoor airflow studies, and model limitations shall be explicitly acknowledged. Uncertainty analysis shall be performed to quantify the influence of boundary conditions, breathing parameters, and emission rates on exposure predictions, ensuring that the CFD results are robust and reproducible.

The following minimum acceptance criteria shall apply:

- Grid independence: the Grid Convergence Index (GCI), evaluated in accordance with ASME V&V 20, shall be ≤ 5 % for primary variables (velocity magnitude and PM2,5 concentration) in the breathing zone, using a minimum of three successively refined meshes with a refinement ratio ≥ 1,3.

- Residual convergence: scaled residuals shall reach ≤ 10^{-4} for momentum and continuity equations, and ≤ 10^{-6} for the energy equation, for steady-state solutions; for transient simulations, equivalent convergence shall be demonstrated at each time step.

- Global conservation: the overall mass and energy imbalance across the computational domain shall be < 1 % of the corresponding inlet fluxes.

- Time-step independence (transient cases): doubling the time step shall not change time-averaged inhaled mass flux in the breathing zone by more than 5 %.

- Validation against reference data: the simulated velocity, temperature, and PM2,5 concentration profiles shall satisfy a factor-of-two agreement (FAC2 ≥ 0,66) and a normalised mean square error (NMSE) ≤ 1,5 at validation locations, evaluated in accordance with established CFD validation protocols for indoor airflow (e.g. COST Action 732 and VDI 3783 Part 9).

The verification and validation report shall document the meshes used, the discretisation schemes, the turbulence and particle models, the boundary and initial conditions, the convergence history, the reference datasets used for validation, and the numerical values obtained for each of the metrics above. Where any criterion is not met, the deviation shall be reported together with a justification and an assessment of its impact on the exposure estimate.

Annex A
(normative)

Algorithm for Indoor-Source Detection and F_{inf} Estimation

A.1 General

This annex specifies the computational procedure for identifying and excluding indoor source dominated periods and for estimating F_{inf} from synchronized indoor and outdoor PM2,5 time series. The procedure is based on the LOWESS-based algorithm of Bi et al. (2021), with the following modifications introduced in the TwinAIR project:

- MAD-based indoor-source event detection, replacing the concentration-percentile selection approach of Bi et al.;
- Moving-Block Bootstrap (MBB) replacing standard bootstrap, to preserve temporal autocorrelation of the time series;
- Seasonal segmentation of long-term datasets to capture variability in infiltration behaviour.

All procedures in this annex shall be applied to datasets that have passed the quality control requirements of Clause 4.4.

The following notation is used throughout:

- $C_{i(t)}$ — indoor PM2,5 concentration at time step t (μg m^{-3});
- $C_{o(t)}$ — outdoor PM2,5 concentration at time step t (μg m^{-3});
- $R(t)$ — indoor–outdoor ratio at time step t (dimensionless);
- $R_{\mathrm{LOWESS(t)}}$ — LOWESS baseline fitted to R(t);
- $e(t)$ — residual at time step t;
- F_{inf} — infiltration factor (dimensionless, range 0–1).

A.2 Outlier detection

A.2.1 General

Prior to indoor-source event detection and F_{inf} estimation, raw LCSs measurements shall undergo a three-stage quality control procedure. The three stages shall be applied sequentially in the order specified below:

- Stage 1: Physical range check;
- Stage 2: Flat-data detection;
- Stage 3: Statistical outlier detection;
- Stage 4: Neighbour correlation.

A.2.2 Stage 1 — Physical range check

Each raw data point shall be evaluated against physically plausible concentration bounds for the deployed sensor type. The upper exclusion threshold shall not exceed the manufacturer-specified measurement range of the deployed sensor. In the absence of a documented manufacturer range, a default upper exclusion threshold of 300 µg m^{-3} shall be applied. In general, low-cost optical particle counters based on light-scattering principles have been shown to exhibit reliable linear responses to PM2,5 concentrations up to approximately 300 µg m^{-3} under typical ambient conditions (Giordano et al., 2021; Barkjohn et al., 2022). Above this range, sensor response becomes increasingly nonlinear, and data shall be interpreted with caution. Consequently, this upper exclusion threshold (300 µg m^{-3}) is consistent with the upper operating limits of commonly deployed low-cost optical sensors.

The following rules apply:

- Measurements with PM2,5 < 0 µg/m^3 shall be set to NaN.
- Measurements with PM2,5 concentrations in the range 0–300 µg/m^3 shall be considered within the reliable linear response range of the sensor and shall be retained for further analysis without modification.
- Measurements with PM2,5 > 1 000 µg/m^3 shall be automatically excluded.
- Measurements with PM2,5 in the range 300–1 000 µg/m^3 shall be flagged for expert review prior to inclusion in the analysis dataset. Such elevated concentrations may arise during intense indoor source events, including cooking and combustion activities, and should not be excluded a priori.

Where supporting environmental sensors are co-deployed, readings outside physically plausible operating bounds for the sensor type — for example, temperature readings above 60 °C or below −10 °C — shall be used as corroborating evidence to invalidate concurrent PM2,5 readings from the same device.

A.2.3 Stage 2 — Flat-data detection

LCSs are prone to several operational issues that can affect data quality, including gradual clogging of the intake fan or measurement chamber due to dust accumulation, transient interference from insects or other foreign bodies entering the optical chamber and scattering light, and the progressive degradation of electronic components. These issues can skew measurements, resulting in prolonged periods of constant or near-constant readings or spurious concentration spikes that do not reflect actual atmospheric conditions.

Sensor clogging or electronic faults can produce extended periods of constant or near-constant readings that are not representative of real atmospheric conditions. A flat detection criterion shall be applied using a standard deviation rolling time window of duration W, checking against a predefined threshold):

$$\sigma\,(\tau, W) < \sigma_{\text{thresh}}$$

where $\sigma\,(\tau, W)$ is the rolling standard deviation of PM2,5 over a window of duration W ending at time t, and is the minimum variability threshold below which a period is considered flat (recommended value: 10 e^{-5} µg m^{-3}).

The recommended window duration is W = 1 h. The chosen value of W shall be documented and applied consistently across all monitoring periods and devices.

Any period during which PM2,5 readings remain constant and successive measurements show no variation — continuously for a duration ≥ W shall be excluded. Both criteria shall be applied independently to indoor and outdoor devices.

A.2.4 Stage 3 — Statistical outlier detection

Following Stages 1 and 2, residual erroneous data points shall be identified using the modified Z-score method. This method uses the sample median and Median Absolute Deviation (MAD) in place of the mean and standard deviation and is therefore robust to the influence of the outliers under detection (Iglewicz and Hoaglin, 1993). The modified Z-score is preferred over the standard Z-score for this application because indoor PM2,5 time-series data from low-cost sensors are typically right-skewed and subject to transient peaks, which would inflate the mean and standard deviation and reduce the sensitivity of standard Z-score detection (Manu and Rysanek, 2024).

For each PM2,5 measurement x_i, the modified Z-score is estimated as:

$$Z_i = 0,6745 \times \left(\frac{x_i - \text{median (x)}}{\text{MAD}_x} \right)$$

where MAD(x) = median ($|x_i$ − median(x)$|$).

Data points with $|Z_i|$ > 3,5 shall be flagged as potential outliers. A threshold of 4,0 has also been applied in co-location studies of low-cost IAQ monitors (Manu and Rysanek, 2024) and may be appropriate where a more conservative flagging rate is desired. Alternative thresholds may be applied where justified by site-specific data characteristics, provided the chosen value is documented and applied consistently.

For long-term deployments exceeding 6 months, the modified Z-score shall be computed within seasonal segments rather than across the full dataset, to avoid masking legitimate seasonal concentration variability. Seasonal segmentation shall be consistent with Clause 4.5.4.

Flagged values though shall not be automatically removed. Each flagged data point shall be subject to expert review before any exclusion decision is made. The review shall consider at minimum the following:

- **Temporal profile:** a legitimate indoor source event — such as cooking, cleaning, or candle burning — typically exhibits a physically plausible rise–peak–decay concentration profile. A sensor fault typically produces an abrupt step-change, a sustained plateau, or a spike with no physical decay. Periods displaying a plausible physical profile shall not be excluded solely on the basis of their modified Z-score.

- **Time of day and occupancy context:** elevated PM2,5 concentrations occurring during periods of known or expected occupant activity shall be interpreted in light of that context.

- **Paired device behaviour:** the concurrent readings of the paired indoor or outdoor device shall be examined. A simultaneous anomaly in both devices may indicate a real atmospheric event rather than a sensor fault.

Following expert review, each flagged period shall be classified as one of the following:

- Confirmed sensor fault: the period is excluded from the dataset and recorded in the data quality log.

- Plausible real-world event: the period is retained in the dataset and recorded in the data quality log with the supporting rationale.

A.3 Indoor-source–dominated period detection

A.3.1 Computation of indoor–outdoor ratio

For each time step t the indoor–outdoor ratio should be computed as:

$$R_t = \frac{C_{i,t}}{C_{o,t-1}}$$

Outdoor concentrations are lagged by one hour to account for the characteristic delay between outdoor fluctuations and the indoor response (Bi et al., 2021).

Only time steps for which $C_{o,t-1}$ exceeds a minimum threshold of 10 µg/m^3 will be retained:

$$C_{o,t-1} \geq 10 \text{ µg m}^{-3}$$

This threshold prevents numerical instability at low outdoor concentrations where the I/O ratio becomes unreliable.

A.3.2 LOWESS smoothing of the ratio

A LOWESS (locally weighted scatterplot smoothing) curve should be fitted to the scatterplot of R_t wit h $C_{o,t}$.

The smoothed function $\hat{R}(C_{o,t})$ represents the indoor/outdoor relationship under infiltration-dominated conditions. The smoother span should be between 50 % and 100 %, and a span of 100 % is recommended.

A.3.3 Residual calculation

For each time step, the residual should be computed as:

$$e_t = R_t - \hat{R}(C_{o,t})$$

A.3.4 MAD-based outlier threshold

The dispersion of residuals should be quantified using the Median Absolute Deviation (MAD):

$$\text{MAD} = \text{median}\ (|e_t - \text{median}\ (e)\ )$$

The MAD is used as a robust measure of dispersion because, unlike standard deviation, it is insensitive to the outliers being detected. An outlier threshold shall be defined as:

$$\text{threshold} = k \cdot \text{MAD}$$

where k = 2,5 is recommended. This value may be adjusted based on site-specific data characteristics, provided the chosen value is documented and applied consistently across all analysis periods.

A.3.5 Flagging and removal of indoor-source events

Any time step for which:

$$e_t > T$$

should be classified as indoor-source–dominated and should be excluded from the dataset used for F_{inf} estimation.

Additional exclusion rules apply:

- e(t) > $k \cdot$ MAD (residual exceeds MAD-based threshold);
- R(t) > 1,2 (I/O ratio indicates dominant indoor source contribution).

C_out_{t-1} < 10 µg/m³ (outdoor concentration below minimum threshold). The resulting dataset should consist only of infiltration-dominated periods.

A.4 Estimation of the Infiltration Factor (F_{inf})

A.4.1 General

Once indoor-source–dominated periods have been removed and the valid infiltration-dominated periods have been identified in accordance with Clause A.2.5, the F_{inf} should be estimated using the procedure described below.

A.4.2 LOWESS regression of the indoor–outdoor ratio

A locally weighted scatterplot smoothing (LOWESS) regression will be fitted on the indoor and outdoor measurements, using only the filtered infiltration-dominated dataset obtained from A.2:

- Independent variable: hourly outdoor PM2,5 concentrations $C_{o,t\text{-}1}$
- Dependent variable: indoor–outdoor ratio

$$R_t = \frac{C_{i,t}}{C_{o,t-1}}$$

The purpose of the LOWESS curve $\hat{R}(C_{o,t})$ is to represent the expected indoor–outdoor relationship during infiltration-dominated conditions.

The smoother span can be between 50 % and 100 %; a span of 100 % is recommended for stability.

This regression is performed only on the filtered infiltration-dominated dataset.

A.4.3 Estimation of the preliminary F_{inf} estimate from LOWESS curve

The infiltration-window selection (Clause A.2) will assure that the dataset reflects conditions where ambient PM2,5 are dominant. Under these conditions, the indoor–outdoor ratio approaches a stable asymptotic value corresponding to the true infiltration factor.

The infiltration factor F_{inf} will be estimated from the upper portion of the fitted LOWESS curve, corresponding to the highest outdoor concentrations remaining after filtering.

No explicit percentile threshold is required.

The infiltration factor will be calculated from the following equation:

$$F_{inf}^{initial} = \text{mean}\ \hat{R}(C_{o,t})$$

With the value being representative of the asymptotic I/O behaviour.

A.4.4 Moving-Block Bootstrap (MBB) for F_{inf}

A.4.4.1 General

To obtain a robust infiltration factor and quantify uncertainty while preserving temporal autocorrelation of the indoor – outdoor P2,5, a Moving-Block Bootstrap (MBB) procedure should be applied.

A.4.4.2 Block construction

The infiltration-dominated time series will be partitioned into overlapping blocks of fixed duration, not shorter than 3 hours; a block length of 6 hours is recommended.

Each block contains synchronized indoor $C_{i,t}$ and outdoor $C_{o,t-1}$ values.

A.4.4.3 Bootstrap resampling

Bootstrap samples of equal duration to the original dataset will be generated by drawing blocks with replacement.

A.4.4.4 Repeated LOWESS and F_{inf} estimation

For each bootstrap sample b:

- Fit a LOWESS curve to the resampled (R_t) dataset.
- Extract a bootstrap infiltration factor as:

$$F_{inf}^{(b)} = \text{mean}\left(\hat{R}^{(b)}(C_{o,t-1})\right)$$

This procedure should be repeated for more than 500 bootstrap iterations with a threshold of M = 1 000 being recommended.

A.4.4.5 Final F_{inf} estimation

The final estimated F_{inf} will be the mean of all bootstrap samples:

$$F_{inf} = \frac{1}{M}\sum_{b=1}^{M} F_{inf}^{(b)}$$

The uncertainty will be quantified using the standard deviation:

$$\sigma_{F_{inf}} = \sqrt{\frac{1}{M-1}\sum_{b=1}^{M} (F_{inf})^2}$$

Annex B
(normative)

Mathematical Formulation of H-CEM

B.1 Transport phenomena

B.1.1 Air Flow of PM2,5

The airflow field is obtained by solving the incompressible Navier–Stokes equations under the Boussinesq approximation for buoyancy-driven flow:

$$\nabla \cdot \mathrm{u}=0 \quad \text{(B.1)}$$

$$\rho\,(\partial u/\partial t + u \cdot \nabla u) = -\nabla p + \mu\,\nabla^2 u + \rho\,g\,\beta\,(T - T\mathrm{ref}) \quad \text{(B.2)}$$

where u is the velocity vector, p the static pressure, ρ the air density, μ the dynamic viscosity, g the gravitational acceleration, β the thermal expansion coefficient, T the temperature, and Tref a reference temperature.

B.1.2 Thermal transport

Thermal effects are modelled using the energy conservation equation:

$$\rho\,cp\,(\partial T/\partial t + u \cdot \nabla T) = \nabla \cdot (k\,\nabla T) + Q \quad \text{(B.3)}$$

where cp is the specific heat capacity, k the thermal conductivity, and Q internal heat generation from occupants and equipment.

B.1.3 Particle transport (discrete phase)

For PM2,5 and ultrafine particles, transport is modelled using a Lagrangian Discrete Phase Model (DPM):

$$mp\,(\mathrm{d}vp/\mathrm{d}t) = \Sigma\,Fp \quad \text{(B.4)}$$

where mp is the particle mass, vp the particle velocity, and Fp includes drag, gravity, and buoyancy forces:

$$\mathrm{FD}=(18\mu/(\mathrm{\rho pdp^2Cc}))(u\text{–}vp) \quad \text{(B.5)}$$

$$\mathrm{FG} = (\rho p - \rho)\ \mathrm{g} \quad \text{(B.6)}$$

Inhalation and exhalation shall be modelled as transient inflow and outflow boundary conditions with a breathing cycle period of 4 s ± 0,5 s.

B.2 Exposure quantification

The instantaneous mass flux of PM2,5 entering the breathing zone is defined as:

$$\dot{\mathrm{m}}\mathrm{in} = \int \mathrm{A}\ C\,u \cdot n\ \mathrm{dA} \quad \text{(B.7)}$$

where C is the volumetric mass concentration of PM2,5 (μg/m^3), A is the mouth or nostril area, u is the airflow velocity vector, and n is the surface normal vector.

The cumulative exposure E(t) shall be computed as:

$$E(t) = \int t\ \dot{m}(t)\ dt \quad \text{(B.8)}$$

Time-averaged exposure shall be reported per respiratory cycle or per unit time (e.g. µg/min).

B.3 Breathing patterns

Table B.1 — Breathing patterns

Population Group	Age Range	Typical Respiratory Rate RR (breaths/min)	Typical Tidal Volume V_T (L/breath)	Derived Minute Ventilation VE (L/min)
Newborn	0–1 month	30–60	6–8 mL/kg (~0,02–0,03 L)	0,6–1,7
Infant	1–12 months	26–60	6–8 mL/kg (~0,05–0,07 L)	1,4–4,3
Child	1–10 years	14–50	6–8 mL/kg (~0,12–0,16 L)	1,7–8,0
Adult male	18–64 years	12–18	~0,50 L	6,0–9,0
Adult female	18–64 years	12–18	~0,40 L	4,8–7,2
Elderly	≥65 years	12–24	0,35–0,45 L	4,2–10,8
Asthma	any	Normal to mildly ↑	Normal to ↓	Normal to mildly ↑

This table highlights how breathing patterns naturally change throughout life. Newborns and infants breathe much faster than adults, but each breath they take is very small. As children grow, their lungs get bigger, their breaths become deeper, and their breathing rate gradually slows down. This balance between breathing rate and breath size helps maintain an appropriate minute ventilation for their body size. In adults, breathing becomes more stable and efficient. Respiratory rate settles into a lower, steady range, while tidal volume is larger. Adult males typically have slightly higher tidal volumes than females, mainly due to differences in average body and lung size. In older adults, breathing can become a bit more variable. Tidal volume may decrease slightly because of reduced lung elasticity and muscle strength, and the respiratory rate may increase to compensate. For individuals with asthma, the breathing rate can be normal or slightly elevated, but the amount of air moved with each breath may decrease because of narrowed airways. Even if the overall minute ventilation looks normal, the airflow limitation can make breathing feel more difficult.

Overall, the table shows how the body adjusts breathing rate and depth across different life stages and how certain conditions, like asthma, can affect this balance.

B.4 Inhalation Exposure Results for Selected Activity Cases (usage as examples)

Table B.2 — Inhalation Exposure Results for Selected Activity Cases

Activity state	Health state	Background pollution (PM2,5)	Gender	Room condition (air velocity, temperature)	Particles reach human nose and mouth
resting	normal	42 (μg/m^3)	man	normal	14(μg/m^3)
resting	normal	42 (μg/m^3)	woman	normal	11(μg/m^3)
walking	normal	45 (μg/m^3)	man	normal	10 (μg/m^3)
Cooking (300(μg/m^3) released in 1 hour)	normal	10 (μg/m^3)	man	normal	127 (μg/m^3)

In terms of outcomes, the table suggests that activity level significantly affects particle inhalation. At rest, men appear to inhale slightly more particles than women, likely due to generally higher tidal volume and minute ventilation. During physical activity such as walking, inhaled particle dose would normally increase because of increased airflow. The cooking scenario clearly shows that indoor emission sources can dramatically raise exposure levels, even when background pollution is relatively low. Overall, the data highlight that inhaled particle exposure depends on a combination of environmental concentration, indoor sources, activity level, and physiological differences.

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