EBENTO

Approximation to ISO 7730 Comfort Indicators

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1. Introduction

The assessment of thermal comfort in indoor spaces is a fundamental aspect to ensure environmental quality and occupant well-being. The ISO 7730 standard establishes a widely accepted reference framework to quantify thermal comfort through the PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied) indices. These indicators allow for an objective description of the expected thermal sensation of a group of occupants and the estimated percentage of dissatisfied users, thereby providing a robust basis for decision-making in building design, operation, and renovation processes.

However, the rigorous calculation of PMV and PPD requires the simultaneous measurement of a comprehensive set of environmental parameters: operative temperature, relative humidity, air velocity, mean radiant temperature, metabolic activity, and clothing insulation level. Among these, air velocity and mean radiant temperature require specific instrumentation, such as dedicated probes, which present significant limitations in long-term monitoring studies due to their cost, size, fragility, and the functional impact associated with installing such sensors over periods of months or years, particularly in residential dwellings.

In practice, most continuous monitoring campaigns conducted in buildings rely exclusively on variables that are easily measurable and stable over time, such as air temperature and relative humidity. This restricted data availability hinders the direct application of ISO 7730 and therefore limits the possibility of obtaining reliable comfort indicators from extended time series.

In response to this situation, it becomes necessary to develop an approximation methodology that enables the inference of PMV and PPD values from conventional monitoring data. To this end, simplified continuous monitoring is combined with punctual in situ measurement campaigns in which a full thermal comfort station is available. These campaigns make it possible to characterise the relationships between continuously monitored variables and the parameters required by the standard, allowing their potential extrapolation to the entire monitored period through statistical models or correlation procedures.

1.1 Valencia demonstrator

The demonstrator is located at Avenida Cataluña, 1 and 3, and consists of two symmetrical 17-storey towers built in 1969. These buildings represent the most common residential building typology in Valencia, corresponding to cluster Bb 1961–1980 according to the building stock clustering system proposed by ERESEE (Long-term Strategy for Energy Renovation in the Spanish Building Sector) [2].

Each building comprises four dwellings per floor. All dwellings share the same layout and are arranged around a central vertical circulation core, rotating in a cross-shaped configuration. This layout is typical of the period and reflects the influence of modernist architectural principles.

At the time of the measurements, Tower B had a fully completed External Thermal Insulation Composite System (ETICS) installed on the façade. In Tower A, the ETICS installation was still ongoing, resulting in partial façade coverage. No roof refurbishment interventions had been carried out in either tower. However, it should be noted that the roof is of a ventilated type and includes an additional over-roof layer, which significantly reduces incident solar radiation.


B
A

2. Approximation methodology

2.1 Measurement campaign

Measurement equipment

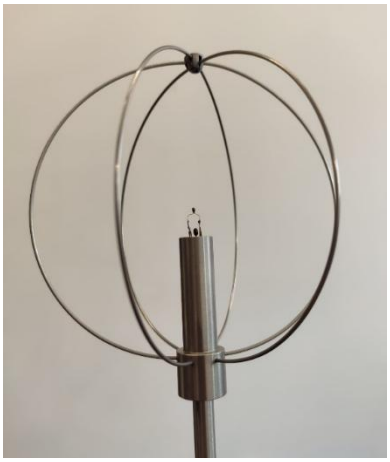
Once the relevant variables and the analytical interpretation of thermal environments according to ISO 7730 had been identified, the different devices used to measure the parameters of the thermal environment were specified. These correspond to the measurement systems for collective environmental factors (CF). Individual environmental factors (IF) are determined within the measurement protocol.

The various devices are installed within the dwellings. In particular, the thermal comfort station is recommended to be located in the living room (Zone 1), while indoor air quality monitoring equipment is installed both in the living room (Zone 1) and in a bedroom (Zone 2). The instruments used are described below.

- TESTO **0636 9743** temperature and relative humidity probe.
  Zone 1. Accuracy: ±0.2 °C; ±1 % RH.



- TESTO **0628 0143** hot-wire air velocity probe in accordance with DIN EN 13779.
  Zone 1. Accuracy: ±0.05 m/s; ±0.5 °C; ±3 hPa.



- TESTO **0602 0743** black globe thermometer (D = 150 mm) for radiant temperature measurement, according to ISO 7243, ISO 7726, DIN EN 27726, DIN 33403.

Zone 1. Accuracy: ±1 °C.



- TESTO **2410899** Testo 480 data acquisition unit, compliant with ISO 7730.
  Zone 1.



In addition, two continuous monitoring probes are installed throughout the year. These sensors are placed in the living room and in an auxiliary bedroom, following the same spatial distribution as the other devices. They measure air temperature, relative humidity, and CO_2 concentration.

- Milesight **AM103** wireless continuous IAQ monitoring sensor.
  Zone 1 and Zone 2.
  Accuracy: CO_2 ±30 ppm + 3%; Temperature ±0.2 °C; Relative Humidity ±2.0%.



Measurement protocol.

Thermal comfort and indoor air quality measurements are carried out in the following locations:

- Zone 1: Main living room of the dwelling. This is the space with the largest volume and highest daily occupancy.
- Zone 2: Indoor air quality control point, located in the main bedroom.

To assess the thermal comfort of the spaces, measurements must be conducted during both the heating and cooling seasons, thereby obtaining an overall evaluation of indoor comfort conditions throughout the year.

During the cooling season, particular attention must be paid to the radiant temperature of surfaces, as these can significantly increase the internal heat load.

During the heating season, special attention must be paid to potential air draughts caused by malfunctioning HVAC systems or insufficient airtightness, as well as to vertical temperature stratification. Among the individual environmental factors, only activity level **(FI_M)**, and clothing insulation index **(FI_{CL})** can be assessed objectively. For activity level, a standard sedentary activity (resting or seated work) is assumed, corresponding to a metabolic rate of 1 met.

For clothing insulation, seasonal values are established to avoid fluctuations that could distort the measurements. Accordingly, a value of 0.5 clo is assumed for the summer season, while a value of 1 clo is used for the winter season.

Measurements are controlled by the data acquisition unit, which is programmed to calculate PMV and PPD values in accordance with ISO 7730 criteria. Data are recorded at 5-minute intervals for a minimum duration of approximately 48 hours per dwelling.

All devices are positioned at a height equivalent to that of a seated occupant



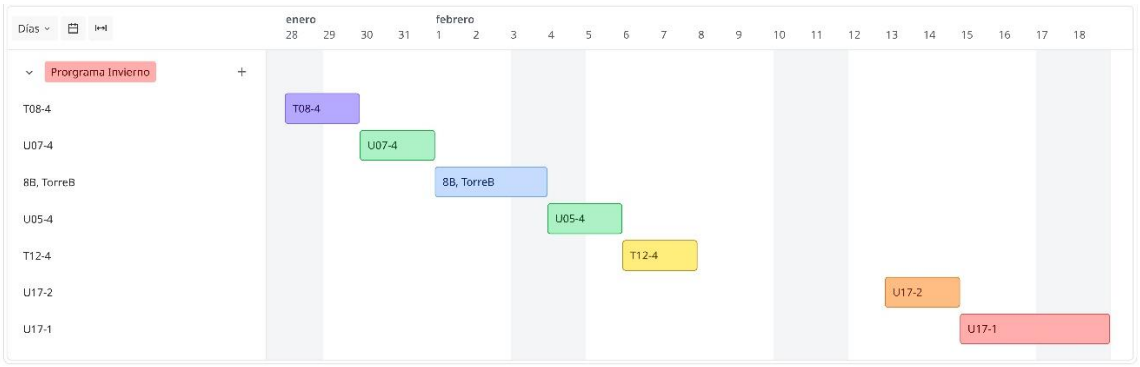


Seasonal measurement programme

To conduct the measurements in accordance with ISO 7730, the two most representative periods of winter and summer were selected. In the climate of Valencia, the coldest winter period typically occurs between late January and early February. The most intense summer conditions are usually experienced between mid-July and early August. However, in the latter case, measurements were brought forward due to limited availability of residents during the holiday period.

Measurements were conducted in continuous periods of at least 48 hours in order to capture, at minimum, one full cycle of thermal inertia charging and discharging of the building. Efforts were made to include a variety of dwelling typologies and usage scenarios, as well as to sequence measurements across dwellings to ensure similar external climatic conditions, within the constraints imposed by resident availability.

The Milesight AM103 continuous monitoring devices recorded data between 2023 and 2025 as part of the continuous monitoring campaign.





2.2 Statistical methodology

To analyse the relationship between the PMV measured in situ and the environmental variables available from continuous monitoring (air temperature and relative humidity), the Real Statistics Resource add-in for Excel was used. This add-in enables advanced multiple linear regression analysis, hypothesis testing, and the calculation of robust standard errors.

First, the datasets obtained from the in situ measurement campaigns were prepared. The selected dependent variable was PMV, obtained using a complete thermal comfort station during punctual campaigns. The predictor variables were air temperature (X1) and relative humidity (X2), corresponding to the parameters available from continuous monitoring.

Considering the P.O. Fanger method used by ISO 7730 for the calculation of the PMV index, it can be observed that this formulation [2.2.a] can be expressed as a linear slope with respect to air temperature, provided that air velocity remains low. An increase in air velocity would modify the behaviour of the function towards a quadratic or exponential form, since convective heat losses (FCv) increase with the square root of air velocity. Therefore, this approximation is only valid for indoor spaces within the demonstrator under low air velocity conditions.

$$(FI_{CL}; FC_{TRM}) \pm (FI_{CL}; FC_{TA}; FC_V) \pm (FI_{RES}; FC_{TA}; FC_{HR}) \pm (FI_E; FI_{CL}; FC_{TA}; FC_{HR}) \quad [2.2.a]$$

The regression analysis was performed with a confidence level of 95%. The classical assumptions of the regression model were evaluated, including standard errors, t-tests, confidence intervals, R^2 and adjusted R^2 statistics, as well as ANOVA. The following heteroscedasticity, normality, and autocorrelation tests included in Real Statistics were applied:

- Heteroscedasticity was examined using the Breusch–Pagan and White tests.
- Residual normality was assessed using the Shapiro–Wilk and D'Agostino–Pearson tests.
- Autocorrelation was analysed using the Durbin–Watson statistic.

As expected, a strong positive autocorrelation was observed, associated with the temporal nature of the data and with lag effects or thermal inertia inherent to indoor architectural spaces. Consequently, a correction using HC3 robust standard errors was applied, adjusting standard errors and p-values to provide more stable inferences under heteroscedasticity and non-normality conditions.

The resulting PMV prediction takes the form of the following equation:

$$P.PMV = CTE + (X_1 * Ta) + (X_2 * HR) \quad [2.2.b]$$

The PPD calculation can be performed in the standard way from the PMV value using the formula defined in ISO 7730:

$$PPD = 100 - 95 \cdot EXP(-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2) \quad [2.2.c]$$

3. Results

3.1 Results of the statistical approximation

The estimated multiple linear regression model exhibits a notably high overall goodness of fit, confirming the strong relationship between the PMV measured in situ and the environmental variables considered: air temperature (AT) and relative humidity (RH).

The multiple correlation coefficient (R = 0.866) and the coefficient of determination (R^2 = 0.7498) indicate that approximately 75% of the variability in PMV can be directly explained by these two variables, which is consistent with the expected physical behaviour of thermal comfort. Furthermore, the adjusted R^2 (0.7497) differs only marginally from R^2, suggesting that the model does not suffer from overfitting despite the large sample size (n = 8,492).

The ANOVA analysis supports the overall validity of the model. The F-statistic reaches an extremely high value (F = 12,722), accompanied by a p-value equal to 0, indicating that the set of predictors contributes significantly to explaining PMV variability. This result confirms that the included variables have a joint effect that is clearly different from zero and that the regression provides substantial explanatory power.

Regarding the model coefficients, air temperature exhibits a positive coefficient (0.3402), indicating that an increase in temperature leads to a direct increase in PMV, as predicted by classical thermal comfort models. Relative humidity, on the other hand, shows a negative effect (−0.0497), which is consistent with the physiological behaviour of the human body, since humidity variations can hinder or facilitate heat dissipation through evaporation, thereby modifying PMV values for the same temperature conditions. Both coefficients present very high t-values and p-values equal to 0, confirming their strong statistical significance even after applying the HC3 robust correction (it should be noted that the composite standard error is 0.56, which is relatively high for the PMV index, whose theoretical range spans from −3 to +3). Confidence intervals do not include zero, further reinforcing their statistical and practical relevance. In addition, VIF values (~3.10) indicate the absence of severe multicollinearity between temperature and humidity.

With respect to model assumptions, the residual normality tests—Shapiro–Wilk and D'Agostino–Pearson—indicate that residuals do not follow a normal distribution. This is common in large environmental datasets due to climatic patterns, seasonal effects, and abrupt variations. Although strict normality is not required for coefficient estimation, it does affect the validity of conventional standard errors, which justifies the use of robust methods.

The Durbin–Watson test reveals a more critical situation: the D statistic (0.013) lies far outside the no-autocorrelation interval, indicating extremely high positive autocorrelation in the residuals. This behaviour is typical of temperature and humidity time series, where consecutive observations are strongly correlated. For this reason, the estimation using HC3 robust standard errors is necessary to prevent autocorrelation from distorting statistical inference.

Finally, heteroscedasticity tests—Breusch–Pagan and White—yield very high LM values and virtually zero p-values, unequivocally confirming the presence of non-constant variance in the residuals. This finding further reinforces the need to employ robust inference techniques, as heteroscedasticity compromises the validity of standard errors and, consequently, of associated t- and p-values.

The predictive PMV equation for all demonstrator cases is as follows:

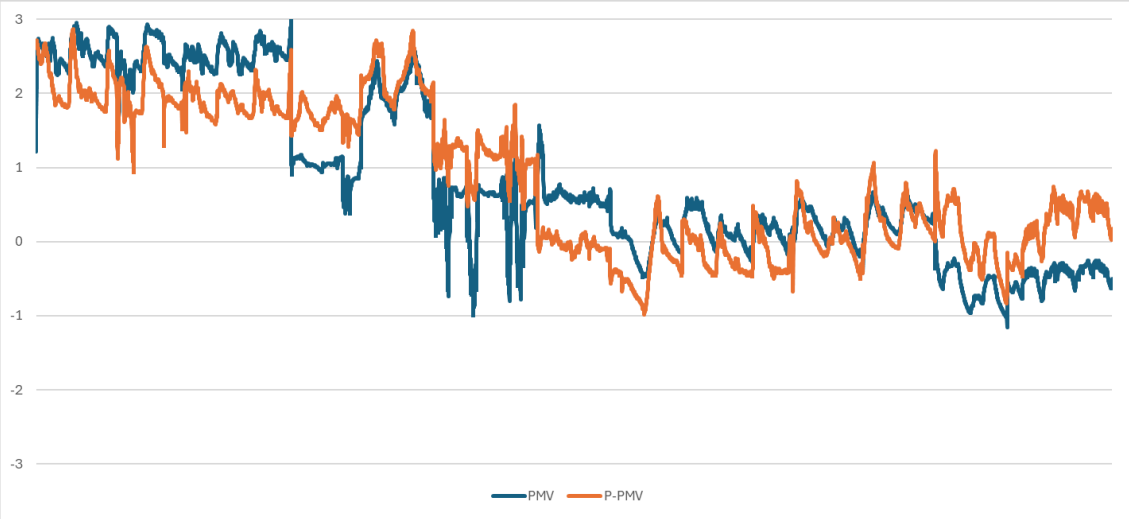
$$P.PMV = -4.39(\pm 0.04) + (0.3401(\pm 0.0026) * Ta) - (0.049(\pm 0.001) * HR) \quad [3.1.a]$$

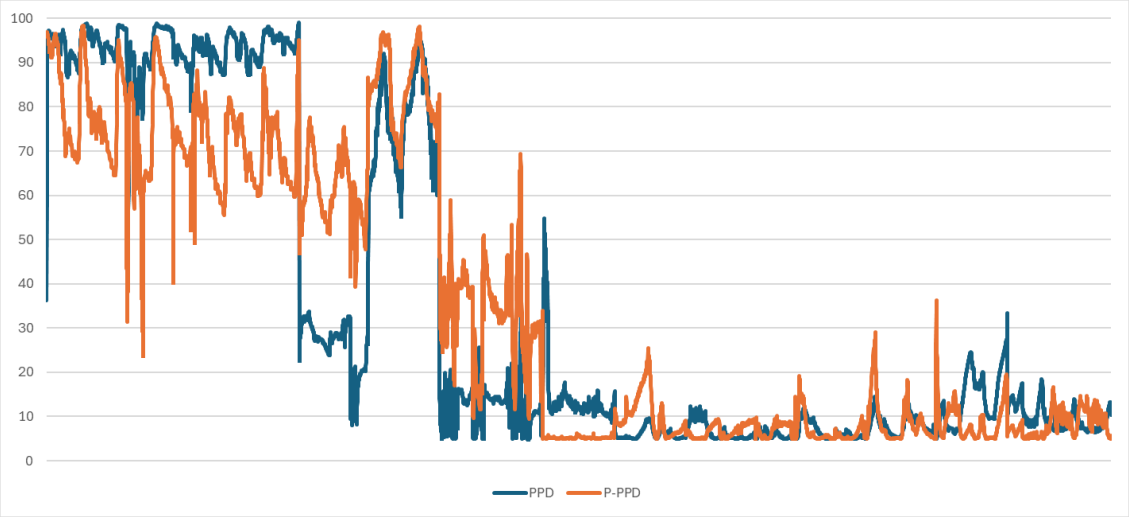
The predictive PPD equation for all demonstrator cases is as follows:

$$P.PPD = 100 - 95 \cdot EXP(-0.03353 \cdot P.PMV^4 - 0.2179 \cdot P.PMV^2) \quad [3.1.b]$$

The PPD fit, which operates as a fourth-order function with respect to PMV deviation, implies a considerable dispersion in predicted PPD values, particularly when PMV values are high. In this case, predictive reliability for PPD decreases from an adjusted R^2 of 0.7497 to an adjusted R^2 of 0.6550, approaching a certain level of risk in terms of result robustness.

The deviations between measured and predicted PMV and PPD values can be observed in the following graphs.

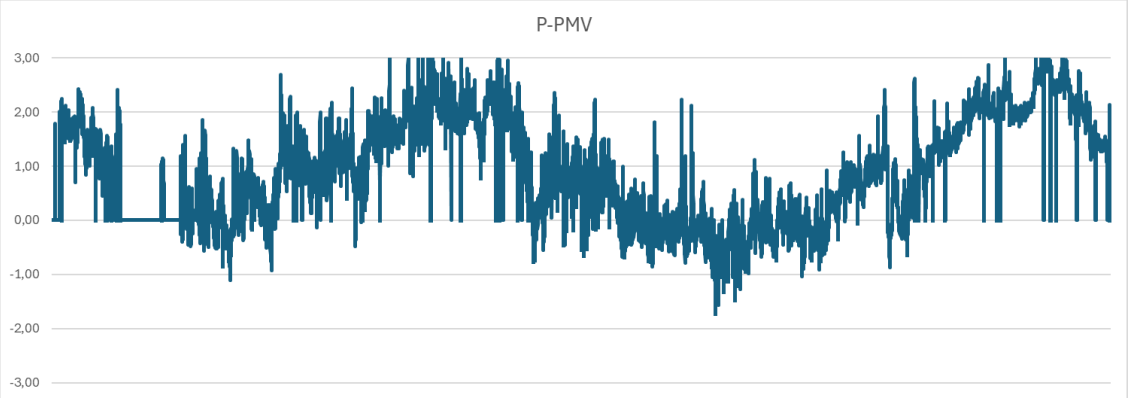




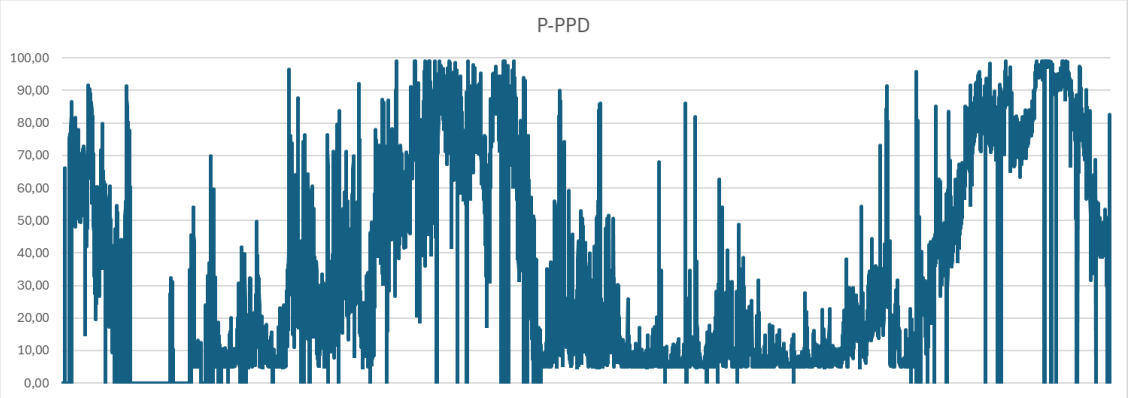
As shown in the previous PPD graph, when PMV values are close to zero, predicted PPD values are consistent with measured values. Considering that the comfort thresholds defined in ISO 7730 range between 5% and 15% dissatisfied occupants, a higher deviation in predicted PPD values at elevated PMV levels does not constitute a methodological limitation, as environments with 50% or 80% PPD lead to the same conclusion: the environment is not comfortable.

3.2 Practical application to a case study

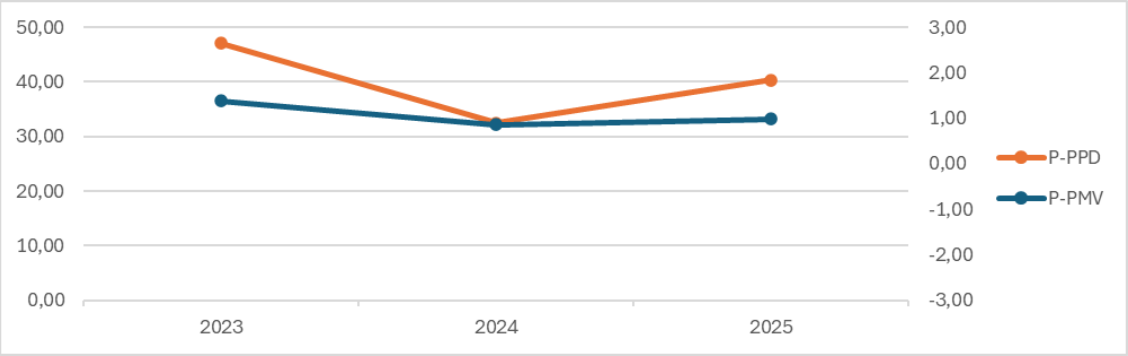
As a representative case study for the application of this methodology, monitoring data obtained since 2023 for sample U05-4 were used. By applying equation 3.1.a to the temperature and humidity data of U05-4, the following P.PMV graph is obtained for the overall monitoring period from 2023 to 2025.



Similarly, by applying equation 3.1.b to the P.PMV data of U05-4, the following P.PPD graph is obtained for the overall monitoring period from 2023 to 2025.



If the comfort evaluation during the measurement programme is analysed, the following graph can be produced:



From the analysis of the above results, it can be concluded that for dwelling U05-4, during the 2023–2025 monitoring period, an improvement in comfort of 28% and 14% was achieved for the PMV and PPD indicators, respectively. A particularly notable improvement is observed in winter performance, while summer behaviour remains largely unchanged, with no perceptible improvement.

4. Conclusions

Overall, the results of the PMV regression model show that it has high explanatory power, coefficients that are consistent with thermal comfort theory, and statistical significance even under HC3 robust estimation. This makes it a useful tool for estimating PMV based on air temperature and relative humidity. However, the strong autocorrelation and heteroscedasticity observed suggest that, while the model is suitable for prediction purposes, it should be interpreted with caution if strict inferential analysis is intended.

Although functional, the methodology requires further refinement and stricter control of its valid application domains. Since PPD is calculated based on PMV, high accuracy in PMV estimation is essential, and additional adjustments are required to achieve at least an R^2 value greater than 90%.

The application to one of the case studies demonstrates an improvement in thermal comfort indicators that is consistent with the energy renovation interventions implemented in the building, confirming a potential positive return in this regard.

Valencia, January 29th, 2026

5. Authorship

This report has been prepared within the framework of the EBENTO project, at the request of OAM València Sostenible, by the Centro de Tecnologías Físicas, Universitat Politècnica de València (UPV).

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Annex A. Calculation operators for Excel

Assuming that this methodology is to be applied to all monitored cases within the demonstrator, and always interpreting results with caution, the equations to be integrated into the outputs of each measurement probe are presented below.

```
Assuming that the temperature column is Column A and relative humidity is Column
B:

Column A = TA
Column B = HR

Decimal separator defined as ","  (format in PowerQuery)

Column C = P.PMV

Formula column C:

=SI.ERROR(0;
       SI(-4.38873775 + (0.34017932*A2)+ (-0.04968119*B2) > 3;
       3;
       SI(-4.38873775 + (0.34017932*A2)+ (-0.04968119*B2) < -3;
              -3;
              -4.38873775 + (0.34017932*A2)+ (-0.04968119*B2)
              )
       )
)

Column D = P.PPD

Formula column D:

= 100 -(95*(EXP((-0,03353*(C2^4))-(0,2179*(C2^2)))))
```