Ministry of Environment

Guidelines for the Deployment and Data Application of Air Quality Sensor IoT Networks

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Abstract

Given the increasing maturity of air quality sensor technologies and the rapid advancement of Information and Communication Technology (ICT) in recent years, the Ministry of Environment (MOENV) continuously promoted environmental sensor IoT projects since 2017. These initiatives aim to transform the national-level air quality monitoring system into a multi-layered, interconnected nationwide network. Due to the widespread application and technical maturity of fine particulate matter ($PM_{2.5}$) sensors, combined with Taiwan's practical experience in air sensor IoT networks, these guidelines provide specific protocols focused on stationary $PM_{2.5}$ sensors. In order to adapt to evolving management models driven by environmental changes and technological advancements, the MOENV will propose innovative recommendations where suitable, and specific operational procedures will be updated based on practical needs.

The scope of these guidelines covers the introduction, sensor performance metrics, pre-factory quality control (QC) procedures, deployment operations, operational management, post-deployment auditing, data publication rules, data application analysis, and derived sensor applications. The introduction describes the overall architecture of the current air sensor IoT network and distinguishes between regulatory monitoring stations, smart city/rural sensor nodes, school-based sensors, and consumer-grade sensors.

The section on sensor performance metrics defines four application tiers: educational use, pollution hotspot identification, personal exposure assessment, and supplemental monitoring for regulatory stations. It defines the application domains, usage constraints, and performance specifications for each tier. For sensors deployed through collaborative projects between the MOENV and local environmental protection bureaus, data must meet performance standards for the "pollution hotspot identification" tier. Regarding pre-factory QC rules, sensors must undergo long-term colocation with reference equipment to establish calibration models and complete type validation before deployment. The deployment rules stipulate that sensor density, height, and siting must be planned based on five major sensing categories to ensure effective data application and analysis. Prior to deployment, all sensors must undergo colocation with regulatory monitoring stations. Once compliance is verified, sensors are installed in accordance with these guidelines. Sensor deployment is categorized into five application scenarios: Industrial, Traffic, Community, Auxiliary, and Special Sensing zones, with ongoing optimization of siting locations. Regarding the operational management section, these guidelines provide recommended procedures, frequencies, and standards for field maintenance, data calibration, sensor clustering analysis, degradation analysis, periodic inspections, anomaly alert management, rapid repair, and equipment replacement. The post-deployment auditing rules outline the recommended procedures, frequencies, and standards for third-party audits, field recall testing, and anomaly inspections.

Through audits conducted by independent third-party entities, these guidelines ensure that sensors continue to meet performance metrics after an extended period of field deployment. Data publication rules specify the standards and responsibilities for releasing sensor data to ensure the accuracy of information provided to the public. The Environmental IoT Platform (IoT Platform for short) is primarily responsible for data collection and validation, while the MOENV AirWeb (WoT Platform for short) focuses on data analysis and supporting smart inspections. To support environmental law enforcement, source apportionment and emergency response big data analytics and AI process collected data to evaluate pollution locations, durations and impact. Derived applications involve extending sensors to mobile platforms and integrating satellite observations or Atmospheric Chemical Transport Models (CTMs) to enhance forecasting capabilities for short-term variations and episodic emissions.

To leverage the advantages of air quality sensor IoT networks while preventing data misuse, these guidelines have been established as a reference for stakeholders and users involved in or interested in sensor network operations. Based on the intended application objectives, these guidelines define performance metrics for supplemental monitoring, personal exposure assessment, pollution hotspot identification, and educational use. Furthermore, they intend to establish operational protocols for sensor siting, deployment, maintenance management, and data quality assurance and control (QA/QC). While ensuring data quality, the objective is to enhance the accuracy and utility of sensor data. Simultaneously, these guidelines inform the public about the limitations of sensor data to prevent misinterpretation, thereby facilitating smart environmental governance and promoting environmental education and awareness.

Table of Contents

List of Tables

List of Figures

Guidelines for the Deployment and Data Application of Air Quality Sensor IoT Networks

Chapter 1: Introduction

In view of the increasing maturity of air quality sensor technologies and the rapid advancement of Information and Communication Technology (ICT), the Ministry of Environment (MOENV) has been implementing environmental sensor IoT projects since 2017. These initiatives aim to establish a multi-layered, interconnected national air quality monitoring network. While air sensors are capable of detecting various pollutants such as $PM_{2.5}$,PM_{10},CO,O_3,NO_2,VOCs , testing results from the Air Quality-Sensor Performance Evaluation Center (AQ-SPEC) of the South Coast Air Quality Management District (SCAQMD) indicate that the data quality for $PM_{2.5}$ is significantly superior to other parameters. Consequently, the MOENV has prioritized the deployment of stationary $PM_{2.5}$ sensors. These are currently deployed across major industrial zones, science parks, traffic corridors, and residential communities to provide continuous sensing of air pollution profiles from regulated facilities. Through big data analytics and artificial intelligence (AI), pollution hotspots and suspect sources can be effectively narrowed down. Supplemented by scientific instrumentation for evidence collection, the efficacy of air sensor IoT networks in supporting environmental law enforcement has been successfully validated. Beyond environmental law enforcement, the network addresses critical public concerns such as monitoring the impact of fire-related pollution, responding to public complaints, and providing health protection for sensitive groups. Real-time local air quality information is accessible via the MOENV website. During episodes of poor air quality, individuals can implement appropriate exposure mitigation measures, such as wearing face masks or utilizing indoor air purifiers. To safeguard personal health and improve air quality in residential or public spaces, ultimately achieving the objective of public health protection.

Taking $PM_{2.5}$ sensors as an example, their simplified sensing principles can lead to discrepancies between sensor data and measurements from regulatory-grade equipment (e.g., regulatory monitoring stations). Due to their low cost and high sensing frequency, these sensors provide minute-level and street-scale data. Furthermore, sensor clusters exhibit excellent precision, and by leveraging their spatiotemporal variability, they can characterize regional pollution patterns. This capability is of significant value in resolving pollution signals within micro-environments.

In the past, a lack of understanding regarding monitoring principles led some members of the public to equate sensor data with that of regulatory monitoring stations. However, the two differ fundamentally in their monitoring objectives, instrument principles, and representativeness (see Section 1.3). Direct comparisons between them can easily lead to interpretative bias. To leverage the advantages of large-scale sensor deployment and real-time monitoring while preventing data misuse, these guidelines have been established as a reference for stakeholders and users involved in air quality sensor IoT operations. Based on the intended use of the data, these guidelines define performance metrics for applications such as: “supplemental monitoring”, “personal exposure assessment’, “pollution hotspot identification”, and “educational use”. They also provide operational protocols for sensor siting, deployment, maintenance management, and data quality assurance and control (QA/QC). While ensuring data quality, the objective is to enhance accuracy and utility. These Guidelines also inform the public about the limitations of sensor data to prevent misinterpretation, thereby facilitating smart environmental governance and promoting environmental awareness and education.

Given the widespread application and technical maturity of $PM_{2.5}$ sensors, combined with Taiwan’s practical experience in air quality sensor IoT networks, these Guidelines provide specific protocols focused on $PM_{2.5}$ sensors for user reference. To adapt to evolving management models driven by environmental changes and technological advancements, the MOENV will propose innovative recommendations as appropriate, and specific operational procedures will be updated based on practical needs.

1.1 Overall Technical Framework

Based on Taiwan's experience in implementing air quality sensor IoT projects and following the order of practical execution, these Guidelines divide the overall technology into six stages: Pre-factory sensor Quality Control (QC), Deployment, Operational Management, Post-deployment Audit, Data Publication, and Application Analysis. The overall technical framework and workflow are detailed in Figure 1, with summary descriptions provided as follows:

1. Pre-factory QC : Equipment manufacturers design and assemble sensors based on sensing requirements, operating environments, and application objectives, establishing sensor calibration models. Finished products must be selected (at least 3 units) and sent to a type validation institution commissioned by the MOENV for testing. Through field evaluation and laboratory testing, various performance metrics for the specific sensor model are verified. For sensors participating in deployment projects co-organized by the MOENV and local environmental protection bureaus, they must meet the performance standards for the "pollution hotspot identification" tier (details on application tiers and performance requirements are provided in Chapter 2).

2. Deployment: Prior to deployment, sensor density, installation height, and siting must be planned based on five major sensing categories to ensure effective performance in future data application and analysis. Before field installation, all sensors must be placed at regulatory monitoring stations near the target environment to undergo colocation between the sensor cluster and the regulatory monitors. Field deployment can only proceed after performance metrics meet the "pollution hotspot identification" tier requirements. Upon completion of the colocation, at least 5% (inclusive) or 6 units (inclusive) or more must remain at the regulatory station to serve as reference equipment for long-term calibration or periodic inspection comparisons. Deployment operations must be executed according to operational rules to obtain representative sensing data while ensuring construction safety.

3. Operational Management: Following deployment, operators must implement regular maintenance and management, including periodic field maintenance, self-conducted inspection colocation, data quality audits, device anomaly management, rapid repair, and equipment replacement. Maintenance and user units should utilize long-term data analysis (including sensor clustering analysis) to determine anomaly events and degradation characteristics, implementing dynamic data calibration to ensure that sensor data quality continuously aligns with the "pollution hotspot identification" tier.

4. Post-deployment Audit: To strengthen QA/QC after deployment, the MOENV (or local environmental protection bureaus) may utilize scheduled or unscheduled

auditing mechanisms. This involves third-party audits, field recall testing, and anomaly inspections to verify that sensors continue to meet the "pollution hotspot identification" tier standards.

5. Real-time Data Publication: For sensors that strictly adhere to deployment and operational management rules, data may be published after verification by local environmental protection bureaus confirming that the data meet the quality requirements for the "pollution hotspot identification" tier.

6. Data Application Analysis: After data collection, organization, and cleaning, big data analytics and AI technologies are applied to analyze spatiotemporal characteristics. This facilitates the evaluation of the location, duration, and impact range of pollution events, supporting environmental law enforcement, anomaly event response, weather system impact assessment, emergency response for heavy pollution episodes, and other applications. These analyses serve as a reference for formulating and implementing environmental governance measures.

Execution Overview	Technical Flow	Requirements and Analysis
Manufacturers design and assemble sensors based on requirements and establish factory calibration models.	Sensor Assembly and Production	Sensing parameters, operating environment, and application objectives.
Sensors are submitted to a type validation platform for evaluation of performance metrics through field evaluation and laboratory testing.	Type Validation	Sensors for collaborative projects with local governments must meet the Pollution Hotspot Identification tier requirements.
Sensor siting and design are planned according to five major sensing categories, including field layout before installation.	Pre-deployment Planning	
Before field installation, all sensors must undergo colocation at regulatory monitoring stations. Field deployment can only proceed after passing this stage. Upon completion, at least 5% or 6 units must remain at the station to serve as references for long-term calibration and degradation analysis.	Colocation → Testing data are uploaded to the IoT platform for MOENV	Collaborative projects must meet the Pollution Hotspot Identification tier requirements.
Sensors are installed based on planned siting and sensing categories to obtain representative data.	Deployment	Post-deployment analysis of siting suitability and operational effectiveness.
Operators must conduct regular field maintenance, self-conducted inspections, anomaly management, rapid repair, and replacement. Data analysis is utilized to ensure data quality continuously aligns with designated performance tiers.	Operational Management	Periodically analyze cloud sensor data to identify device anomalies, environmental anomalies, or sensor degradation, and implement dynamic data calibration.
Management and user units conduct quality control for deployed sensors, including third-party audits, field recall testing, and anomaly inspections to strengthen data quality management.	Post-deployment Auditing	For collaborative projects, data quality must meet the Pollution Hotspot Identification tier standards.
Data from sensors managed according to deployment and maintenance rules may be published if they meet the Pollution Hotspot Identification tier requirements.	Real-time Data Publication	Sensor data upload, sensor operation and maintenance (O&M) and data refinement, data quality auditing by local environmental protection bureaus, and MOENV supervision.
Use big data analytics to support environmental law enforcement, respond to anomaly events, assess weather system impacts, and provide emergency response for heavy pollution episodes.	Data Application Analysis	Utilize the spatiotemporal variation characteristics of sensor data to analyze the location, timing, and impact range of events, serving as a basis for formulating environmental governance measures.

(Deployment through Data Application Analysis →) Formal sensor data is uploaded to the MOENV IoT Platform and then transmitted to the MOENV WoT Platform for real-time visualization and support of smart inspections

Figure 1. Overall Technical Framework and Workflow of the Air Quality Sensor IoT Network

1.2 Information and Communication Technology (ICT) System Architecture of the Air Quality Sensor IoT Network

The overall ICT system architecture of the air quality sensor IoT network is illustrated in Figure 2. Upon acquiring environmental data, air quality sensors transmit information via 4G LTE or NB-IoT wireless communication systems to data collection centers maintained by vendors. These centers are primarily categorized into two types: cloud-based virtual machines (VMs) and vendor-owned on-premises server rooms. The processed data is then used by the MOENV AirWeb (WoT Platform) for pollution event analysis and notification alerts. The platform provides map-based dynamic visualization of air quality data. The entire system must strictly comply with relevant information security regulations.

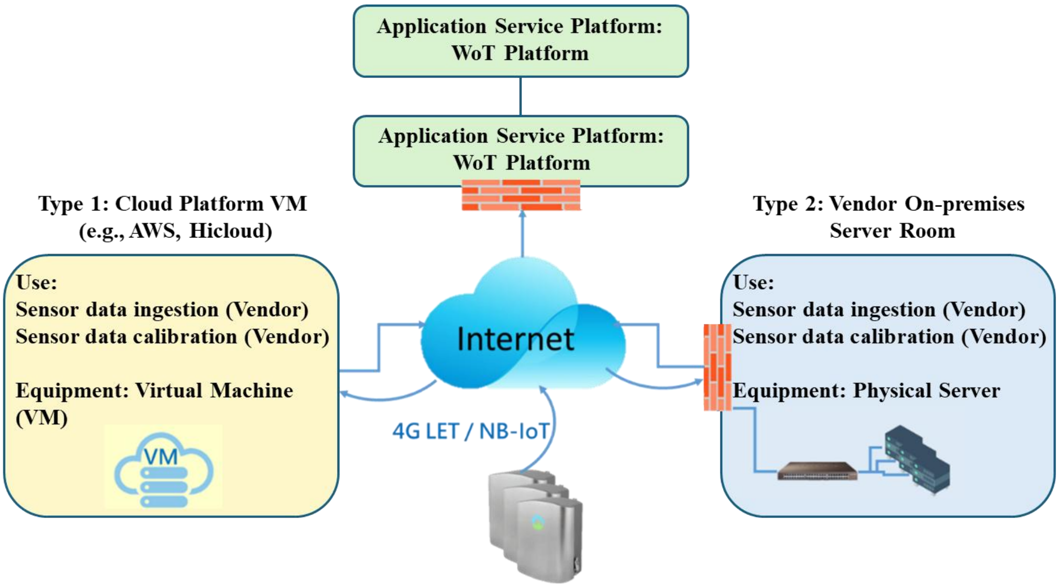

Figure 2. Label Translations

1.3 Differences Between Sensors and Regulatory Monitoring Stations

Due to their sensing principles and methodologies, air sensors are susceptible to environmental interference, leading to discrepancies between sensor data and measurements from regulatory-grade equipment. It is essential for users to understand the limitations of sensor data applications to prevent data misuse. Common domestic sources of air quality information include: regulatory monitoring stations, smart city/rural sensor nodes (air sensors deployed through MOENV-local government collaborations), school-based sensors, and consumer-grade sensors. The fundamental differences between these sources are explained in Table 1

Table 1. Comparison Between Sensors and Regulatory Monitoring Stations

Type / Item	Regulatory Monitoring Stations	Smart City/Rural Sensor Nodes (Air quality sensors deployed through central and local government collaborations)	School-Based	Consumer Sensors
Monitoring Objectives	Regulatory monitoring	Pollution hotspot identification	Environmental education	Personal & home applications
Data Applications	Regional AQ standard compliance; law enforcement; transboundary transport analysis	Small-scale hotspot identification and emission source tracking	Relative trends in micro-environments and exploratory cause analysis	
Instrument Principles	Beta attenuation monitoring (BAM) or inertial mass method	Physical light scattering		
Particle Size Definition	**Aerodynamic diameter:** Equivalent diameter based on aerodynamic behavior	**Optical diameter:** Measured via laser scattering; affected by particle surface and humidity		
Health Risk Correlation	Currently, health risk studies and standard reference methods are based on aerodynamic diameter.	The correlation between optical diameter and health risks has not yet been established.		
Spatial Resolution	Approx. 10–25 km	100–300 m (Industrial); approx. 1 km (Others)	Varies by deployment density	
Temporal Resolution (Particulate Matter / PM)	1 hour	1–3 minutes	1–5 minutes	
Temporal Resolution (Gaseous Pollutants)	1 minute	1–3 minutes	N/A	Varies by model
Usage Constraints	1. Lower distribution density makes it difficult to track local pollution sources. 2. Automated monitoring data require regular calibration. 3. Operation requires specialized professional training. 4. Siting is restricted by height and obstruction requirements, differing from typical residential environments.	1. Conversion between optical and aerodynamic diameters involves inherent errors. 2. Light sources are prone to dust accumulation over time, leading to performance loss. 3. Measurements are highly susceptible to interference factors (e.g., humidity). 4. High data variability; values may show significant discrepancies compared to regulatory stations. 5. Data may not represent true ambient air quality; sensor quality is inconsistent.		
Relationship with AQ Standards	1. Health risk research regarding fine particulate matter ($PM_{2.5}$) air quality standards (e.g., in Japan and the U.S.) focuses exclusively on 24-hour and annual averages—specifically 35μg/m^3 (daily) and 15μg/m^3 (Japan) / 9μg/m^3 (U.S.) (annual). There are currently no recommended limits for very short-term (hourly or minute-level) exposure concentrations. Consequently, hourly measurements from automated regulatory monitoring stations and minute-level data from sensors cannot be directly interpreted through these air quality standards to assess health risks. 2. The U.S. EPA has officially incorporated the "Sensor Scale" into its "Air Sensor Toolbox" and integrated it with the AirNow Fire and Smoke Map platform. This framework provides health interpretation tiers (e.g., Low, Moderate, High, and Very High) for			

Type / Item	Regulatory Monitoring Stations	Smart City/Rural Sensor Nodes (Air quality sensors deployed through central and local government collaborations)	School-Based	Consumer Sensors
	1-minute instantaneous $PM_{2.5}$ data, supported by a national correction equation. This initiative is designed to assist the public in understanding health risks from very short-term exposure and is not intended to serve as a regulatory basis to replace the National Ambient Air Quality Standards (NAAQS).			
Siting Requirements	Stringent; based on the Enforcement Rules of the Air Pollution Control Act.	Industrial zones, major traffic routes, or communities without regulatory stations. Requires ventilation, power, and connectivity.	Sheltered balconies with good ventilation within school premises.	Sheltered residential areas with good ventilation.
Installation Height	10 meters high	3 meters high	Mostly on the 1st floor (approx. 2–3 m)	Uncertain
Maintenance Frequency	Weekly, bi-weekly, monthly, and quarterly maintenance	Quarterly inspection once	None or unscheduled	
Installation and Maintenance Costs	Very High	Moderate	Low	
Instrument Certification or Third-party Testing	Internationally certified by organizations such as the United States Environmental Protection Agency	Industrial Technology Research Institute Laboratory and Field Testing	Industrial Technology Research Institute Laboratory and Air Quality-Sensor Performance Evaluation Center Testing	Varies by model
Error Range (Bias)*	< 10%	< 30%	Raw data avg. error ~50%#; extremes up to 100%	Varies by model
Intra-model Variability	---	IMV < 10%	IMV < 10%	Varies by model
Pre-deployment Calibration	Complies with international certification standards	Unified factory calibration; pre-deployment colocation at regulatory monitoring stations.	Unified factory calibration	Varies by model
QA System	Yes	Yes	None (uses backend anomaly detection algorithms)	
QA Performance Audit	Yes; annually	Annual 10% random audit	None	
QC Functional Check	Yes; six times per year	Quarterly inspection once	Direct replacement after 1.5 years	None

＊Due to the absence of primary standards, absolute accuracy cannot be determined; performance is expressed as relative bias compared to regulatory-grade instruments.

＃Academia Sinica, the Ministry of Environment, and school-based sensor manufacturers are jointly conducting research on backend calibration for sensor data。

Chapter 2: Sensor Performance Metrics

The performance of $PM_{2.5}$ sensors depends on their capability to measure air pollutant concentrations. To assist users in achieving their specific monitoring objectives, and by referencing international recommendations on sensor performance alongside Taiwan's practical application experience, the following sections in this chapter provide recommended performance metrics for various sensing purposes. These recommendations aim to guide users in selecting appropriate equipment and obtaining reliable sensing data.

2.1 Tiered Classification of Sensor Application Objectives

Sensor applications are categorized into four domains: (Level 1) educational use, (Level 2) pollution hotspot identification, (Level 3) personal exposure assessment, and (Level 4) supplemental monitoring for regulatory Stations. Table 2 outlines the data usage constraints for each application domain. These recommended principles are established based on current operational experience and will evolve alongside scientific and technological advancements.

Table 2. Tiered Classification of Sensor Application Objectives

Tier	Application Domain	Application Details and Description	Data Usage Constraints	Applicable Locations
Level 1	Educational Use	• Measurement equipment with relatively large error ranges and lower data credibility, yet still capable of representing air pollution trends in the sensing area. • Suitable only for general public science education for citizens lacking specialized pollutant knowledge.	• Sensing errors are larger than Level 2, resulting in lower credibility; however, data maintain a similar trend to ambient concentrations. • Only suitable for illustrating relative pollutant trends within an area; data cannot represent absolute ambient concentrations.	• Schools
Level 2	Pollution hotspot identification	• Deployed near suspect emission points to identify potential sources. • Utilizes sensor clusters to monitor spatiotemporal trends, narrowing down hotspots and analyzing peak pollution times to support source identification.	• Less reliable than Level 3 or 4 but effective for identifying relative concentration deviations. • Data should not be released directly to the public without implementing data QA/QC protocols; once data publication rules are met, information can be provided for public reference. • Best used for generating color-coded concentration	• Industrial zones • science parks • industrial clusters • public complaint hotspots • major traffic routes

Tier	Application Domain	Application Details and Description	Data Usage Constraints	Applicable Locations
			maps to interpret regional air quality variations.	
Level 3	Personal Exposure Assessment	• Monitors air quality during normal daily activities. • Sensors are worn by clinically sensitive individuals to identify exposure timing, locations, and the potential health impacts of specific pollutants.	• Numerous factors affect individual exposure to air pollutants. The **precision** and **bias** standards for this tier are based on scientific research reports. • If errors exceed these standards, it becomes difficult to analyze the mode, timing, and causes of individual exposure.	• Hospitals
Level 4	Supplemental Monitoring for Regulatory Stations	• Installed in areas not covered by existing national networks to provide supplemental concentration gradient information. • Under comprehensive QA/QC mechanisms, sensor data can serve as reference data for ambient concentrations.	• When maintained under a complete QA/QC framework and meeting third-party audit standards, the generated data can supplement the national monitoring network and provide public reference data for ambient concentrations.	• Regions without regulatory monitoring stations

2.2 $PM_{2.5}$ Sensor Performance Metrics by Application Tier

1. Definition of Parameters

(1) Data Completeness (DC, %): The expressions are presented as follows:

$$\text{Data Completeness(DC)}=\frac{N_{valid\ data}}{N_{total\ data}}\times 100\%$$

Where $N_{valid\ data}$ is the number of valid sensor data points during the test period, and $N_{total\ data}$ is the total number of expected data points during the test period.

(2) Relative Error (%) / Relative Bias (%): These metrics evaluate the discrepancy between sensor readings and reference instrument measurements. The expressions are presented as follows:

- Bias = Sensor Reading - $Reference\ Reading$
- Relative Bias = (Bias / Reference Reading) × 100%

- Relative Error = (|Bias| / Reference Reading) × 100

- Assessment of Relative Bias (%): The median of the relative bias values calculated at each time point during the test period.

- Assessment of Relative Error (%): The median of the relative error values calculated at each time point during the test period.

(3) Standard Deviation of Relative Error/Bias (STD, %): This measures the degree of dispersion in the relative error (or bias) between the sensor and the reference instrument. The expressions are as follows:

$$\mathrm{STD}(\%) = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n}}$$

Where n is the total number of data points, x_i is the relative error (or bias) at a specific time point, and $\bar{x}$: is the mean relative error (or bias) over the test period.

(4) Linear Regression: A linear regression analysis is performed between sensor readings and reference readings using the following model:

$$\mathrm{Y} = \mathrm{aX} + \mathrm{b}$$

Where Y represents the sensor reading and X represents the reference reading.

A. Coefficient of Determination (R^2): The square of the Pearson product-moment correlation coefficient, used to explain the linearity of the relationship between variables on the X and Y axes.

B. Slope: The slope of the line of best fit from the linear regression.

(5) Intra-model Variability (IMV, %): Assesses the consistency of measurement results across different units of the same sensor model. The expressions are presented as follows:

$$\mathrm{IMV}(\%) = \frac{Mean_{highest} - Mean_{lowest}}{Mean_{average}} \times 100\%$$

Sensors are deployed in triplicate for data collection.

$Mean_{highest}$: Represent the highest mean values among the three units at each time point, respectively.

$Mean_{lowest}$: Represent the lowest mean values among the three units at each time point, respectively.

$Mean_{average}$: The overall mean of the three units.

Assessment of IMV (%): The median of the intra-model variability values calculated at each time point during the test period.

(6) Precision (P, %): Evaluates the relative standard deviation of the sensor across different concentration levels. The expressions are presented as follows:

$$\mathrm{P}(\%) = \frac{S}{\bar{x}} \times 100\%$$

$$\mathrm{S} = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}$$

Where:

- S ：Standard deviation of sensor readings at a certain concentration equilibrium state.
- $\bar{x}$ ：Average value of sensor readings at a certain concentration equilibrium state.
- x ：Sample reading of the sensor at a certain concentration equilibrium state.
- n ：Number of times the sensor readings were sampled at a certain concentration equilibrium state.

(7) Coefficient of Variation (CV): Evaluates the consistency of readings across a cluster of sensors. The expressions are presented as follows:

Root Mean Square Deviation (RMSD_i)= $\sqrt{\frac{\sum_{t=1}^{\rho}(x_{i,t}-x_{avg,t})^2}{\rho}}$

Where $x_{i,t}$ is the reading of the i-thsensor at a given unit time, $x_{avg,t}$ is the average reading of all sensors in the cluster at that time, and ρ is the number of data points.

$$\text{Variation Coefficient } (CV_i) = \frac{RMSD_i}{\overline{X_{avg,t}}}$$

$$\text{Overall Mean of } x_{avg,t}\ (\overline{X_{avg,t}}) = \frac{\sum_{t=1}^{\rho}(x_{avg,t})}{\rho}$$

2. Performance Metrics by Application Tier

To assist users in selecting appropriate sensors for different monitoring objectives, the US EPA has defined performance metrics for 4 application tiers. The requirements and descriptions for each tier are summarized in Table 3.

Table 3. US EPA Air Sensor Performance Metrics by Tier

Tier	**Application Domain**	**Pollutant**	**Precision and Bias Error**	**DC**
Tier 1	Educational Use	All	< 50%	＞50%
Tier 2	Hotspot Identification	All	< 30%	＞75%
Tier 3	Supplemental Monitoring	Specific	< 20%	＞80%
Tier 4	Personal Exposure	All	< 30%	＞80%

The MOENV has also referenced the US EPA tiered performance metrics for air sensors, integrating Taiwan's practical experience in $PM_{2.5}$ sensor deployment and the continuous refinement of data calibration and comparison technologies to further establish Taiwan's $PM_{2.5}$ sensor performance metrics by application tier. Compared to the US EPA, the performance metrics regulated by the MOENV are more stringent (as shown in Table 4) to provide sensor users and the public with more credible air quality monitoring information. Taking the sensors deployed through collaborations between the MOENV and local environmental protection bureaus as an example, the primary objective is to assist local bureaus in conducting smart inspections. Therefore, the Quality Assurance and Quality Control (QA/QC) requirements across all stages—including pre-factory performance QC, deployment, operational management, post-deployment auditing, and data publication rules—stipulate that sensor data must meet the performance metrics for the Level 2 "pollution hotspot identification" tier.

Table 4. Taiwan MOENV $PM_{2.5}$ Sensor Performance Metrics by Level

Level	Application Domain	DC	Error	STD	R^2	Slope	IMV	CV
Level 1	Educational Use	＞60%	< 50%	< 50%	＞0.70	0.50~1.50	< 20%	< 20%
Level 2	Hotspot Identification	＞90%	< 25%	< 30%	＞0.80	0.75~1.25	< 10%	< 10%
Level 3	Supplemental Monitoring	＞90%	< 15%	< 20%	＞0.85	0.85~1.15	< 10%	< 10%
Level 4	Personal Exposure	＞90%	< 10%	< 10%	＞0.90	0.90~1.10	< 10%	< 10%

Chapter 3: Pre-factory Performance Quality Control Rules

The effectiveness of the Air Quality Sensing IoT depends on the stability of front-end sensors and the accuracy of data. Before executing deployment operations, selecting appropriate sensing components based on the characteristics of different pollutants and conducting standardized performance testing and calibration are essential procedures to ensure monitoring quality. Through rigorous screening requirements for sensor hardware specifications, interference from environmental factors on values can be reduced, providing sensing data with significant reference value. This chapter focuses on defining the various performance quality control operations that should be executed from the time sensors leave the production factory until deployment. By establishing unified performance testing indicators, it ensures that sensing equipment can produce stable spatiotemporal data that meets environmental governance needs during long-term operation.

3.1 Sensor Functional Specifications

Sensor performance requirements vary by application. Since data quality depends on basic performance, operational methods, and analysis techniques, understanding the advantages and limitations of sensors is critical for their intended purpose. Recommended functional specifications for outdoor environmental sensing and pollution hotspot identification are provided as follows:

1. Sensing Module: The primary parameter is Fine Particulate Matter ($PM_{2.5}$), with a sensing frequency of one data point per minute. Users may install additional components such as temperature, humidity, wind speed, wind direction, ozone (O_3), carbon monoxide (CO), nitrogen dioxide (NO_2), and VOCs based on field requirements. However, sensing performance must be capable of detecting the local concentration ranges and must be validated by a reliable testing institution.

2. Communication Module: Modules can be selected based on local conditions but must support rapid extraction and replacement. Data transmission modules should be chosen to optimize real-time complete transmission and cost-efficiency. To ensure data stability, it is recommended to avoid LoRa modules and prioritize more stable continuous transmission modules such as 3G, 4G, or Wi-Fi.

3. Power Module: Design should be energy-efficient, featuring voltage stabilization

and various power conversion designs to ensure uninterrupted operation and data transmission. If installed on street lamps where power may be unavailable during the day, storage devices must comply with electrical safety standards for nighttime charging and daytime operation. For mobile monitoring tasks in areas without utility poles, solar modules and energy storage (typically lithium batteries) are recommended, provided they comply with the following regulations:

(1) Design qualification and type approval for solar modules must comply with CNS 15114 or CNS 15115 regulations.

(2) Structural safety and testing requirements for solar modules must comply with CNS 15118-1 and CNS 15118-2 to ensure long-term outdoor safety.

(3) If solar modules are installed long-term in coastal or high-salinity areas, they must comply with CNS 15196 regarding salt mist corrosion testing.

(4) Lithium batteries must utilize modules that have passed safety certifications (IED62233, UN38.3, BSMI CNS 15364, or equivalent). They must also include internal overheat protection circuits and voltage monitoring chips to prevent potential fires caused by overheating.

4. Microcontroller and Data Storage Unit: Devices should feature data processing, large-capacity storage, and component status detection and notification. Capabilities for remote cloud-based resetting and operational status monitoring are required to support equipment maintenance management or replacement.

5. Modular Design: Sensor modules must be modular to facilitate the rapid replacement of components or the addition of new sensing parameters. Design must ensure the rationality of intake and exhaust channels for each component. Modularity should support future expansion via circuit board expansion slots or external Universal Serial Bus (USB) interfaces.

6. Sensor Body Design: The mechanical design must be waterproof for outdoor use (recommended minimum of IP55 rating). The intake sampling mechanism should provide stable and unobstructed flow to prevent pollutant accumulation or reaction delays. The design should resist interference from environmental wind fields and minimize the impact of wind speed on intake flow. To ensure data

quality and performance auditing, intake ports for sampling and calibration should be designed to support test gas calibration and future automatic calibration module testing.

7. Information Security: Communication and system security specifications must comply with the requirements of the government, application units, or relevant jurisdictions. It is recommended that communication modules or microcontrollers feature Over-the-Air (OTA) firmware update encryption and device authentication mechanisms to prevent unauthorized intrusion or data hijacking.

3.2 Pre-factory Sensor Calibration

Following sensor production and assembly, although sensing components include factory calibration parameters, factors such as the design of the intake sampling module, regional environmental variations, and interactions between components will affect data presentation. Therefore, a series of quality control and calibration procedures must be performed before the equipment leaves the factory. In addition to ensuring the precision of sensing behavior among sensors of the same model, the error between the sensor and standard instruments (e.g., regulatory monitoring stations) must meet the performance metrics of the designated application tier. This requires long-term comparison with reference standard equipment to establish an appropriate calibration model, thereby providing users with reliable sensing data.

1. Sensor Interference Factors: Based on domestic and international literature as well as practical experience in Taiwan, the known interference factors causing data bias in $PM_{2.5}$ sensors are as follows:

   (1) Sensing components are significantly affected by weather conditions such as ambient humidity, temperature, and wind speed. The composition, particle size, and surface characteristics of suspended particles in the environment also influence sensing principles, leading to data bias. Therefore, sensor calibration must be adjusted according to the deployment area to align with local environmental and pollution characteristics.

   (2) Since sensed concentration is derived from the number of pollutants within a unit volume of intake air, the sensor's intake method and flow rate are critical

factors causing biases in concentration interpretation. High ambient wind speeds that reduce intake flow will result in a negative concentration bias; similarly, aging or clogged intake fans that decrease intake efficiency are also primary causes of negative concentration bias.

(3) Due to high atmospheric dispersion efficiency, the response time of the sensor to pollutants is essential for real-time sensing. If the design of the sensor's intake sampling mechanism is inadequate, it will fail to perform its function in pollution hotspot identification.

2. Sensor Precision: Practical experience has shown that $PM_{2.5}$ sensors exhibit excellent group consistency. The primary characteristic is that measurements from a cluster of the same sensor model remain highly consistent within the same environment. Equipment vendors utilize this test as the primary control basis for pre-factory QC. Generally, sensors from the same production batch are placed in a steady-state environment for comparison over a period. The variability of readings from each sensor must be lower than the group variability requirements to pass quality control standards, typically evaluated using Root Mean Square Deviation (RMSD), Coefficient of Variation (CV), and the Coefficient of Determination (R^2).

3. Sensor Data Calibration: Known interference factors for $PM_{2.5}$ sensor measurements in field environments include humidity, temperature, and wind speed. Due to simplified sensing principles, discrepancies occur between sensor data and measurements from standard methodology equipment. Therefore, data conversion and calibration must be performed immediately after production to analyze correlations between the sensor and environmental impact factors. Through long-term parallel comparison with reference instruments (e.g., $PM_{2.5}$ monitoring equipment at regulatory monitoring stations), a multivariate calibration model is established to reduce biases between the sensor and reference instruments, ensuring compliance with performance metrics for the designated application tier. However, once sensors are placed in the field, factors beyond changing climatic conditions—such as component contamination, degradation, and changes in intake system efficiency—will affect data bias. Consequently, the post-factory calibration model requires dynamic adjustment over time to ensure continuous compliance with tiered performance metrics.

3.3 Sensor Type Validation

To ensure the development of the air quality sensor IoT network and the appropriate utilization of data produced by sensors, the Ministry of Environment (MOENV) evaluates performance characteristics such as accuracy and precision for sensors intended for field deployment. This process also provides manufacturers with a platform for product research, development, and calibration testing, effectively assisting the industry in enhancing its technical capacity. In 2018, the MOENV commissioned the Center for Measurement Standards of the Industrial Technology Research Institute (ITRI) to conduct air quality sensor performance testing and validation (detailed operational descriptions are available at https://airsensortest.blogspot.com/). The testing service platform and execution procedures reference the equipment and methodologies of the Air Quality-Sensor Performance Evaluation Center (AQ-SPEC) established by the South Coast Air Quality Management District (SCAQMD) in California, USA.

1. Field Evaluation:

   (1) Measurement Duration: A minimum of one week of continuous measurement (7 days × 24 hours).

   (2) Reference Instrumentation: $PM_{2.5}$ reference instruments must be equivalent to or better than the United States Environmental Protection Agency Federal Reference Method (FRM) for manual sampling or the Federal Equivalent Method (FEM) for automated monitoring. These instruments must be verified by the MOENV quality assurance protocols to meet required standards.

   (3) Valid Data Count for Reference Instruments: Using $PM_{2.5}$ hourly concentrations as the unit of count, low-concentration data (e.g., values below 10 μg/ m^3) are excluded. Sufficient high-concentration data must be obtained (e.g., at least 5% of data must exceed 36 μg/ m^3). After deducting invalid entries, the proportion of valid continuous measurements must be at least 90% (inclusive). If the number of data points is insufficient, the comparison period may be extended.

   (4) Testing Parameters: Evaluation must include Intra-model Variability (IMV) for the same model, Data Completeness (DC), the Coefficient of

Determination (R^2) relative to reference instruments, and Relative Error (Error, %).

(5) For $PM_{2.5}$ sensor field evaluations, the performance metrics for tiered application assessment must, at a minimum, include Data Completeness, Relative Error, Coefficient of Determination (R^2), Linear Regression Slope, and Intra-model Variability (IMV).

2. Laboratory Testing:

(1) Test Conditions: Sensor performance testing is conducted within a laboratory environment. By regulating control factors such as wind speed, temperature, relative humidity, and mass concentration, the precision and bias between the sensor and reference instruments are evaluated once a steady-state condition is achieved.

(2) Reference Instrumentation: $PM_{2.5}$ reference instruments must be equivalent to or better than the United States Environmental Protection Agency Federal Reference Method (FRM) for manual sampling or the Federal Equivalent Method (FEM) for automated monitoring. These instruments must be verified by the MOENV quality assurance protocols to meet required standards.

(3) The laboratory system can regulate various fine particulate matter concentrations, as well as the temperature and relative humidity within the test chamber. This is used to evaluate parameters such as Intra-model Variability, Data Completeness, Coefficient of Determination (R^2), Precision, bias error, temperature, humidity interference effects, and the limit of detection (LOD). In principle, the primary regulation range for fine particulate matter concentration must cover low, medium, and high ranges (e.g., 0 to 300 $\mu g/m^3$). A total of seven or more parameters are evaluated during this testing activity.

(4) For $PM_{2.5}$ sensor laboratory tests, the performance metrics for tiered application assessment must, at a minimum, include Data Completeness, Relative Error, Coefficient of Determination (R^2), and Linear Regression Slope.

(5) In field environments, sensors are affected not only by temperature and

humidity but also by wind speed, which significantly interferes with intake efficiency. Therefore, the laboratory system must regulate wind speed within the test chamber to evaluate the interference effects of different wind speeds on the sensor.

(6) Due to the rapid rate of atmospheric dispersion, sensors must respond to high pollution concentrations in real-time to avoid missing regional pollution events. The response lag time for high concentrations should be shorter than the effective sensing interval (e.g., within 1 minute).

Chapter 4: Operational Deployment Rules

The value of the sensing IoT lies in compensating for the spatial coverage limitations of regulatory monitoring stations. By providing a comprehensive map of air quality changes in microenvironments through high-density site configuration, it enhances monitoring capabilities. To effectively leverage the benefits of sensing data in environmental governance, the deployment process must be planned by combining local pollution characteristics and meteorological conditions to enhance the representativeness of site placement and data quality. This chapter describes the logic for site selection and the principles of deployment, assisting relevant units in configuring sites based on the needs of industrial areas, communities, or specific pollution hotspots. Through standardized installation processes and environmental considerations, the operational stability of sensors is strengthened, ensuring a reliable basis for subsequent data analysis and auxiliary smart enforcement functions.

4.1 Sensor Siting Planning

Air pollutants exhibit high spatiotemporal variability, and under the high dispersion efficiency of the atmosphere, meteorological conditions in micro-environments dominate the dispersion behavior of pollutants. In addition to continuously improving sensor precision and enhancing inspection and maintenance efficiency, leveraging the advantages of sensors—such as ease of large-scale, high-density deployment and high-frequency sensing—to plan optimized deployment areas and sensor nodes can effectively improve the resolution of environmental pollution behavior.

To effectively utilize air sensors for environmental governance, application scenarios include industrial pollution source identification, community characteristics near emission sources, traffic sensing in urban areas, supplemental sensing in townships without regulatory monitoring stations, and special sensing considering seasonal meteorological conditions. Based on different application objectives and site characteristics, representative, beneficial, and feasible sites (considering communication and power) are selected and categorized into five major sensing types, described as follows:

1. Industrial Sensing Nodes: Used to monitor factory-dense areas for source apportionment and environmental law enforcement. Deployment density is

recommended at intervals of 50–300 meters.

2. Traffic Sensing Nodes: Used to monitor high-traffic areas, primarily for assessing the pollution distribution of mobile sources like cars and motorcycles along traffic corridors. Project-specific deployment is conducted for specific road segments based on monitoring needs, with a recommended density not exceeding 1 kilometer.
3. Community Sensing Nodes: Primarily focused on communities near large pollution sources, such as those within 2 kilometers of industrial zones, with a recommended deployment density of 100–500 meters. For other general communities, a grid-based deployment with a 1–1.5-kilometer density is recommended to serve as a reference for the public's daily life.
4. Supplemental Sensing Nodes: Installed in sparsely populated townships or districts without regulatory monitoring stations. For example, these may be combined with wind speed and direction measurements from meteorological stations to serve as environmental background references.
5. Special Sensing Nodes: To bring sensor siting closer to public living areas, specific regions can be included for evaluation, such as public complaint areas or sensitive receptor sites like hospitals. Deployment and usage should be adjusted according to seasonal wind directions.

In addition to planning sensor nodes for specific areas of concern, to effectively track sensor service life, it is recommended to reserve at least 5% (inclusive) or 6 units (inclusive) to be placed at nearby regulatory monitoring stations for long-term comparison (refer to Section 4.3). Continuous data collection and the establishment of inspection and adjustment protocols are required for data calibration and monitoring performance degradation. These units can also serve as reference backups for inspections or replacements.

4.2 Sensor Siting Principles

Beyond meeting application requirements, the safety and convenience of subsequent construction, maintenance, and management are key assessment principles for selecting sensor nodes. Given that large-scale sensor deployment involves significant construction, maintenance and operation costs, the preliminary siting principles are summarized as follows:

1. For long-term sensing nodes, to avoid the influence of mobile pollution sources and ensure the convenience of construction and maintenance, a sensor installation height of 3–5 meters are recommended, which may be adjusted based on actual field conditions.
2. For traffic sensing nodes designed to observe mobile pollution sources, the installation height is recommended to be below 1.5 meters to prevent high atmospheric dispersion from making it difficult for the sensor to reflect pollution behavior from vehicle emissions.
3. Because sensors require stable power and communication, sites that facilitate land and power access are preferred to optimize deployment and maintenance and operation cost-effectiveness. Street lamp poles or utility poles are the optimal installation options, with metal poles being superior to concrete poles or wall-mounted installations due to construction convenience. Regarding power usage, consent must be obtained from the authorities responsible for power and lamp poles, and relevant electrical safety regulations must be strictly followed.
4. When selecting lamp poles for sensor installation, factors such as installation convenience, inspection suitability, and maintenance and operation feasibility must be considered. The recommended siting criteria are as follows:
   (1) Locations with convenient parking to facilitate the use of aerial work platforms during construction.
   (2) A clearance of at least 1meter around the lamp pole to facilitate installation and maintenance.
   (3) Lamp poles with a normal power supply, where usage rights can be obtained from the street lamp management and maintenance and operation units.
   (4) Lamp poles on both sides of the road are preferred; poles on central dividers or safety islands are less suitable due to difficulties in maintenance and operation and traffic control, which hinder construction and maintenance.
   (5) No obstructions, such as trees or signboards, should be within a 1-meter radius of the sensor installation to avoid affecting the sensor's intake

efficiency.

(6) Pollution emission sources, such as temple incense burners, restaurant exhaust vents, or driveway entrances/exits, should be avoided within 50 meters of the sensor installation site, as these will lead to sensing data being directly affected by localized pollution sources.

5. The recommended siting sequence follows the basic principle of an equidistant grid, starting from primary areas of concern (such as industrial zones) and expanding outward to surrounding communities. The network then extends toward high-density urban areas or areas with frequent public complaints, spreading from proximity to pollution sources and sensitive receptors to the peripheral regions.

4.3 Full Sensor Colocation

Before field deployment, all sensors must be mounted at regulatory monitoring stations for parallel comparison. Colocation is conducted across sensor batches; the following description uses the Pollution Hotspot Identification tier as an example:

1. Data Validity Requirements: Continuous colocation must last for at least 5 days (inclusive). For regulatory monitoring stations, the total valid count of $PM_{2.5}$ hourly values must reach 90% (inclusive) or higher. For individual sensors, the total valid count of $PM_{2.5}$ minute-level readings must be at least 70% (inclusive), with at least 42 valid readings per hour (≥70%). Sensor data measured during periods where ambient concentrations are below 10 $\mu g/m^3$ may be excluded. If data from either the station or sensors fail to meet these validity requirements, the comparison period may be extended to achieve the required number of valid data points.

2. Colocation Requirements: The colocation process consists of two stages: Stage 1 requires that the Relative Error (Error, %) between each individual sensor and the regulatory monitoring station meets the requirements for the Pollution Hotspot Identification tier to ensure acceptable bias, Stage 2 focuses on the consistency of the sensor cluster by calculating the Coefficient of Variation (CV); the cluster's CV must meet the Pollution Hotspot Identification tier standards before the sensors can be sent to the field for deployment. For the performance standards corresponding to the Pollution Hotspot Identification tier, please refer to the

content of Table 4 in Section 2.2.

If it is not possible to compare all sensors simultaneously, testing should be conducted in batches. For example, after completing the first batch comparison, 10% of those sensors should remain to participate in the second batch to ensure inter-batch consistency; this methodology should be applied sequentially to subsequent batches.

Additionally, upon completion of the full colocation, it is recommended to leave at least 5% (inclusive) or 6 units (inclusive) or more at the regulatory monitoring station to serve as references for long-term calibration against the station, while facilitating observations of sensor degradation and service life. These units serve as reference equipment (also known as reference sensors) for periodic inspections. Furthermore, if a sensor deployed in the field is damaged, its replacement must first undergo colocation with the reference sensors reserved at the regulatory monitoring station and meet all requirements before onsite installation.

4.4 Sensor Installation

To obtain representative sensing data, the sensor installation process must ensure both construction safety and accurate siting. During installation, it is necessary to verify the surrounding environment for any factors that might interfere with precise measurements. Key installation considerations are summarized as follows:

1. Implement contractor management protocols. Clarify the scope of work, responsibilities, and authorities with the contracting unit. Conduct briefings on construction safety, electrical safety, key equipment installation points, and the rights and obligations of all parties.
2. Conduct field layout for sensing nodes prior to installation. The construction unit must verify the installation locations and inventory all necessary tools, equipment, and accessories.
3. Implement safety education and alcohol screening prior to construction. Record the names and contact numbers of the on-duty construction personnel; each construction team must consist of at least two members.
4. Upon arrival at the installation site, verify the street lamp pole number and the planned installation height. Conduct onsite traffic management and place traffic cones.

5. Capture photographs before, during, and after construction. Record the sensor node station number and the street lamp pole number.
6. Power on the sensor before installation to verify that operations and data upload functions are normal before proceeding with field installation.
7. It is recommended to use a standard height pole (e.g., a 3-meter rod) to mark the sensor installation height and the position for power wiring.
8. Personnel shall secure the sensor to the lamp pole. Upon completion, verify that the sensor is firmly fixed to prevent the risk of loosening or falling.
9. Configure the power connection between the sensor and the street lamp:
   (1) Construction work must comply with relevant government laws and regulations. Operations must follow electrical safety standards and be performed by personnel holding valid licenses from qualified electrical distribution authorities.
   (2) Power wiring must adhere to safety standards for electrical distribution. Insulation work must be complete, and power cables should be equipped with protective sleeves or relevant protection and securing fixtures.
   (3) A residual current circuit breaker (RCCB) must be installed at the feed point between the street lamp power source and the sensor. The installation height should avoid damp areas.
   (4) After wiring is complete, verify that the main power is switched on, the sensor is connected to the external power supply, and sensor data upload is functioning normally.
   (5) Complete waterproofing protection for the power connections of the street lamp, sensor, and wiring to ensure the safety of the entire system's operating power.
10. Inventory all construction tools, related equipment, accessories, and consumables. Clean the construction site before removing the traffic cones.

4.5 Siting Optimization Review

Although there are recommendations for deployment density and height for industrial, traffic, community, supplemental, and special sensing nodes, regional pollution characteristics change over time. To ensure the spatial representativeness of the monitoring network and the efficiency of resource allocation, it is necessary to conduct long-term observations of sensor data behavior and evaluate the application objectives and benefits of existing sensors. It is recommended to conduct a siting optimization analysis and rolling adjustment of sensor deployment at least once a year to install sensors at appropriate locations based on local conditions.

Taking the optimization of siting for pollution hotspot identification as an example, the necessity and effectiveness of nodes can be analyzed based on the frequency of pollution events at existing deployment sites. If adjacent sensors show similar responses due to location and environmental characteristics, only representative nodes should be retained, while redundant nodes are removed to streamline the scale of deployment. Considering special needs such as general communities, public complaint hotspots, or areas with concentrated sensitive populations like hospitals, the environmental correlation between the area of concern and surrounding high-pollution sources should be assessed. Under the influence of prevailing seasonal winds, node deployment should be planned upwind of the concern area to provide early warnings to local residents and evaluate the health impact of pollution on sensitive groups.

Based on the needs of local environmental protection bureaus, the primary application scenarios for sensor deployment include source apportionment in factory-dense areas, monitoring and emergency response for the impact range of fire-related pollution within the jurisdiction, tracking and improving public complaint events, and health protection for sensitive groups. Recommendations for optimized deployment siting are provided as follows:

1. Source Apportionment in factory-dense areas: Following the deployment density for industrial sensing nodes, planning is recommended at intervals of 50–300 meters, with an average of one node every 200 meters. Once the range of a pollution hotspot is confirmed, deployment density can be increased to 50–100 meters for detailed source apportionment.
2. Monitoring and Emergency Response for Fire Pollution Impact: Based on deployment experience, sensors can generally reflect pollution concentrations within a 1-kilometer radius. Therefore, for fire accidents within the jurisdiction,

a deployment density of 2 kilometers is recommended, specifically covering the fan-shaped area downwind of the fire-intensive zone.

3. Tracking and Improving Public Complaints: Reference can be made to public complaint data from the MOENV and demographic data from the Ministry of the Interior. Siting should be planned upwind and downwind based on the pollution characteristics of the complaint hotspot. It is recommended to deploy one node within 50 meters downwind of the complaint location, with comparison points deployed more than 200 meters upwind and downwind of the complaint location to track pollution sources.
4. Health Protection for Sensitive Groups: For deployment in areas where sensitive populations are concentrated (e.g., hospitals, schools, parks), it is recommended to install sensors adjacent to these areas. This provides micro-environmental concentration reference data to prompt the public to implement health protection measures

Chapter 5: Operational Management Rules

The quality of sensing data directly affects the needs of subsequent analysis and application. Therefore, during the operation and maintenance management process, the history of maintenance and servicing must be recorded in detail to serve as a reference for evaluating the sensor's life cycle, performance characteristics, signs of degradation, and failure features. Regarding basic operation and maintenance data, the specifications for the sensing components and functional modules within each sensor must first be established. These include the brand and model of the sensing components and their operating time, the calibration procedures and operation manuals provided by the original manufacturer, the recommended sensing range, precision, bias, and limits, as well as information on the optimal sensing frequency, response time, service life, and factors that may cause interference. Key recommendations for the operational management of sensors used for pollution hotspot identification are provided as follows.

5.1 Reasons for Sensing Data Bias During Operation

In addition to being easily affected by weather conditions such as environmental humidity, temperature, and wind speed, known reasons for data bias in $PM_{2.5}$ sensors during long-term, high-frequency environmental sensing operations are as follows:

1. Accumulation of environmental dirt leads to degradation of the sensitivity and performance of the sensing components, resulting in bias in the sensing data.
2. Long-term operation causes the sensor's intake system mechanism to become dirty or clogged, resulting in a reduction in intake flow and causing the sensed concentration readings to be low.
3. Changes in the sensor's surrounding environment may also affect sensing data, such as airflow blockage caused by tree growth or newly erected billboards.
4. Aging of sensing components or performance degradation of auxiliary mechanisms may both be reasons affecting sensing data drift.

To ensure the quality of a large amount of long-term sensor data, regular maintenance management is critical. This includes regular cleaning of internal mechanisms such as intake filter components, intake fans, and intake channels; sensing components and sensing chambers must be kept clean. Other items, such as functional checks of batteries and circuit boards, also require attention. As for regular inspections of the sensor's surrounding environment, objects that may affect smooth airflow, such as tree groves or newly erected billboards, must be cleared or moved. Therefore, after long-term operation of the sensor, the sensing performance must continue to be observed through regular inspection mechanisms, with regular comparison and calibration to maintain the quality of the sensor's data.

5.2 Regular Field Maintenance

To reduce data bias caused by sensors being placed on field environments for long periods of time, user units or operation and maintenance vendors should establish regular maintenance management mechanisms. By observing the regional characteristics of cluster sensing data over the long term and referencing regular field maintenance records, sensing nodes with similar sensing characteristics should be categorized into clusters based on the environmental features of the deployment area to establish long-term cluster sensing behavior analysis models. Taking the requirements for the Pollution Hotspot Identification application tier as an example, it is recommended that user units or operation and maintenance vendors conduct onsite visual inspections for each sensor at least every 3 to 6 months. The focus of these inspections is as follows:

1. Check the environment surrounding the sensor, the sensor's exterior, and related components (such as mounting components and external power systems).
2. Conduct internal inspections of the sensor mechanism and, if necessary, perform cleaning for filters, intake channels, sensing chambers, fans, and sensing components.
3. To maintain the effectiveness of the sensing environment, inspect whether new obstructions (such as overgrown vegetation or newly erected billboards) have appeared within a 1-meter radius of the sensor's perimeter and clear or relocate them.
4. Inspect whether new pollution emission sources, such as temple incense burners, restaurant grease exhaust vents, or driveway entrances/exits, have appeared within 50 meters of the sensor's surroundings. If the sensor is easily affected directly by local pollution sources and these sources cannot be eliminated, an evaluation should be conducted for sensor relocation.

Visual inspections and maintenance cleaning should each have image and text records established and linked with cluster sensing data. Through the accumulation and analysis of long-term records, automated operation and maintenance management mechanisms can be developed, effectively reducing the frequency of field operations while maintaining sensor operational quality. To enhance sensor operation, maintenance, and inspection efficiency, onsite visual inspections and periodic inspection comparison operations (as detailed in Section 5.6) can be performed simultaneously.

5.3 Sensor Data Calibration

The primary interference factors for $PM_{2.5}$ sensing elements in field measurements include humidity, temperature, and wind speed. Even under the operation of effective maintenance and servicing mechanisms, sensing data will still exhibit bias. Therefore, sensors must undergo continuous data calibration after leaving the factory to analyze the correlation between the sensor and environmental impact factors. Calibration mechanisms can effectively enhance sensor data quality, significantly increasing the correlation between sensing data and reference instruments. Through long-term parallel comparison with reference instruments (e.g., $PM_{2.5}$ monitoring equipment at regulatory monitoring stations), multivariate calibration models are established to help ensure that the bias between the sensor and the station data meets the tiered performance requirements. At the same time, after deployment in the field, regular or dynamic calibration is required to maintain data quality; it is recommended that data calibration be performed at least once a month. If data quality still does not meet the standards for the pollution hotspot identification tier, the calibration frequency should be increased. Shortening the calibration cycle helps provide timely corrections for sensor zero drift and sensitivity degradation, thereby ensuring long-term monitoring quality. Furthermore, the temporal resolution of the sensing data to be calibrated must be adjusted to match the temporal resolution of the reference instrument. Taking calibration against regulatory monitoring station data as an example, since the station's temporal resolution is hourly, the sensing data to be calibrated must be converted from minute-level to hourly values before calibration to ensure synchronization with the reference instrument data. Multiple linear regression is listed below as an example for illustration:

1. Independent variables: Independent variables available for calibration models include sensor readings, regulatory monitoring station temperature, station relative humidity, station wind speed, sensor temperature, sensor relative humidity, and sensor wind speed. Other reference variables may also be considered, provided that independence between variables is ensured. Since low-cost sensors mostly use light-scattering principles for monitoring and are highly susceptible to humidity interference, it is recommended that operation and maintenance units prioritize analyzing the functional relationship between relative humidity and sensor concentration bias to establish humidity compensation mechanisms, thereby reducing the interference of ambient humidity on data interpretation.

2. Cluster calibration methods: Under the condition of meeting precision requirements, cluster sensors can establish a calibration model based on regulatory monitoring stations by selecting representative sensors and installing them at regional stations for long-term comparison. This calibration model can then be applied to other sensors within the cluster. However, the following items should be noted:

    (1) In principle, the more independent variables a calibration model considers, the better the resulting data quality will be. However, it is essential to ensure the independence of the variables used and that these variables maintain a certain level of data quality. For instance, if sensor-derived temperature, relative humidity, and wind speed data are used as independent variables, the quality of those specific sensing data must be carefully monitored. While data from regulatory monitoring stations provide stable data quality, they may not be suitable for application to sensors located too far from these stations. Therefore, the following methods are recommended for data calibration:

        A. Place sensors for long-term comparison at nearby regulatory monitoring stations (or those with the same environmental background) to establish calibration expressions. Using the station as a center, establish different sensor subsets from nearest to farthest, and perform data calibration layer by layer. If the calibration results are still not as expected after incorporating temperature and humidity factors, it is recommended to add simple anemometers to the representative sensors of each subset to include meteorological conditions in the calibration expressions, thereby improving data calibration quality.

B. Mobile air quality monitoring vehicles or simple $PM_{2.5}$ standard instruments (such as MetOne, etc.) that meet data quality standards can be deployed to the site for sensor data calibration.

(2) Longer parallel comparison periods result in better reference value for the established calibration models. However, the applicable concentration range for the calibration model should ideally be the ambient concentration range measured during parallel comparison; therefore, it is not recommended to apply the calibration model outside the analyzed concentration range.

(3) To improve the reliability of calibration models, dynamic calibration is recommended. For example, regularly adjust the calibration model by accumulating comparison data from the previous two weeks, one month, or the previous year (the latter is less recommended as it cannot account for component degradation) to establish the calibration model for the next stage.

(4) Since the linear relationship between sensors and regulatory monitoring stations varies across different concentration ranges, it is recommended to define linear relationships for different concentration intervals through long-term comparison analysis. Since regulatory monitoring stations provide hourly average concentrations while sensors provide minute-level averages, high-concentration responses are very likely near pollution sources. If linear extrapolation is used for concentration calibration, the error will increase. Therefore, for calibration models exceeding the values of regulatory monitoring stations, it is recommended to establish high-concentration environments through human intervention or laboratory simulation to serve as a more reliable reference for short-term high-concentration sensing data calibration.

(5) To further improve sensor data quality, individual calibration modes for each sensor can be established in the future. The initial calibration can be achieved through parallel comparison with regulatory monitoring stations, while subsequent calibrations can be performed through cluster analysis of group

sensing data. Periodically, reference instruments (or reference sensors) that meet tiered performance metrics can be brought to the sensor cluster for parallel comparison calibration, combining cloud-based data calibration with physical calibration to enhance the data quality of each sensor.

5.4 Sensor Cluster Analysis

Due to the large-scale deployment of sensors in field environments, mechanisms for equipment information, smart inspection, data calibration, and degradation analysis should be established to ensure the continuous provision of credible data. By collecting sensing data over the long term and analyzing trend variations, the operational quality of sensing equipment can be interpreted, and signs of degradation or failure can be analyzed. This effectively reduces the management and control costs of the sensor IoT network and enhances the service quality of sensing data.

Because $PM_{2.5}$ sensors possess excellent precision, they not only reflect the reproducibility of pollutant sensing concentrations in identical environmental conditions but also demonstrate consistency across group sensing data when multiple sensors are placed in the same environment. Therefore, when examining signs of abnormality in field-deployed sensing equipment, the behavior of a group of sensors should exhibit significant consistency within areas of similar environmental characteristics, provided there is no influence from localized pollution events. By categorizing similar groups into the same cluster and periodically analyzing the variability within that cluster, the abnormal characteristics of a sensor can be identified. Analysts may select appropriate analysis methods (such as Euclidean distance, Ward's method, agglomerative hierarchical clustering, or artificial neural network algorithms) or suitable statistical software (e.g., Statistical Product and Service Solutions, SPSS) to perform cluster analysis.

1. Excluding invalid sensing data: When a sensor experiences missing values, constant values, negative values, or values exceeding the sensing range for a period (e.g., 1 hour), it should be classified as an equipment failure state and excluded from cluster analysis. The operation and maintenance unit should follow equipment repair protocols to complete troubleshooting within a specified timeframe.
2. Cluster partitioning: Through the collection of historical sensor data, cleaning and

excluding abnormal data and outliers, and performing environmental and big data analysis, sensors with similar sensing behaviors are incorporated into the same cluster. A minimum of three sensors (inclusive) is the basic requirement for cluster analysis. Based on historical analytical experience, sensors can reflect pollution concentrations within a 1-kilometer radius. Therefore, it is recommended that cluster analysis observe two types of measurement differences to determine cluster groupings: (1) Grouping by spatial distance: Sensors within a 1-kilometer radius are grouped together. (2) Grouping by sensing behavior correlation: Behavior correlation analysis is performed among sensors within a 1-kilometer radius. Decisions are generally based on positive correlation shown by the Coefficient of Determination (R^2), with groups showing the most distinct positive correlations being formed into a cluster. (3) Grouping by seasonal influence: Since sensing behavior is significantly affected by seasonal wind directions, cluster partitioning must consider seasonal impacts, typically evaluating and grouping by summer and winter wind directions. To ensure that cluster classifications reflect current environmental backgrounds and deployment changes, it is recommended to re-perform cluster partitioning at least once a year.

3. Cluster variability analysis: Through consistency or correlation analysis between individual sensors and the sensor cluster, screening weights for sensor abnormalities are categorized based on the degree of variability and frequency of occurrence Screening metrics may include the Coefficient of Determination (R^2), Coefficient of Variation (CV), and Relative Error (Error). Combined with the frequency of abnormal sensor behavior patterns, environmental variability compliance, field maintenance verification, and the assistance of AI technology, a smart cloud-based anomaly diagnosis model and automated cloud inspection mechanism are gradually established. To implement sensing data quality control, it is recommended to conduct cluster variability analysis at least once a quarter to capture sensor degradation or abnormal states in a timely manner.

4. After cluster analysis identifies a sensor abnormality, the status should be clarified through relevant information or field verification within a set period. If it is an equipment abnormality, troubleshooting should be completed through equipment maintenance mechanisms; if it is an environmental abnormality, the pollution inspection mechanism should be followed to track pollution characteristics and

complete environmental law enforcement.

5. Through periodic cluster analysis results, cloud inspections are performed to identify outliers in each subset. When many outliers are discovered, if the cause can be directly identified and resolved within the database, there is no need for a field visit. Conversely, if a sensor problem is discovered that requires onsite handling, it can be addressed immediately without waiting for issues to be found during routine inspection comparisons. This approach not only saves significant human and material resources but also shifts periodic (onsite) inspections to frequent (cloud-based data analysis) inspections. This better ensures the reliability of air quality sensor monitoring data and significantly reduces the manpower required for the operation and maintenance of numerous air sensors.

5.5 Sensor Degradation Analysis

Sensors conduct high-frequency sensing in field environments. The primary reasons for the increase in sensing data bias include the fouling or aging of sensing components and a reduction in intake efficiency (such as dirt or blockage in the intake system and decreased intake fan efficiency). To observe whether sensors exhibit degradation behavior, judgments can be made through the long-term observation and analysis of trends in the correlation, bias, and standard deviation between the sensor and reference instruments. Since ambient $PM_{2.5}$ concentrations vary by season, long-term trend comparisons should account for seasonal differences as well as trend variations within the same time periods across different years.

1. Use sensors deployed at regulatory monitoring stations for long-term trend analysis. Analyze the trends in correlation or bias between the sensors and the stations, and interpret the degradation trends of that specific batch model based on the correlation between trend variations and time progression.

2. Conduct long-term trend analysis for sensor clusters in the vicinity of regulatory monitoring stations (e.g., within a 1-km radius, depending on the sensors and environmental conditions). Analyze the trends in correlation or bias between the sensor clusters and the stations, and interpret the degradation trends of the sensor clusters based on the correlation between trend variations and time progression.

3. Using regulatory monitoring stations as a benchmark, analyze the long-term trends in correlation or bias between sensor clusters and the stations. Interpret the

cluster sensor degradation trends based on the correlation between variations in the sensing concentration range and time progression.

4. For sensors located far from regulatory monitoring stations, it is recommended to conduct long-term trend analysis using reference instruments (or reference sensors) and sensor clusters. The data quality requirements for reference instruments (or reference sensors) are the same as those for periodic inspections (as detailed in Section 5.6). Analyze the trends in correlation or bias between the sensor clusters and the reference instruments (or reference sensors), and interpret the degradation trends of the clusters based on the correlation between trend variations and time progression

5.6 Periodic Inspections

To maintain data quality of sensors, user units or operation and maintenance vendors should establish periodic inspection plans to efficiently manage large numbers of sensors. Operation and maintenance units can categorize groups with similar sensing behaviors into the same cluster based on regional environmental characteristics. By utilizing the consistency of cluster sensor behavior under stable environmental conditions, abnormal sensors can be identified, and the unique characteristics of cluster sensing anomalies can be analyzed to screen for equipment failures or sensors with sensing deviations. This is followed by periodic inspection operations to clarify the causes of anomalies, evaluate the need for field inspection and calibration, or confirm failure causes for maintenance, servicing, and equipment updates. Taking the requirements for the Pollution Hotspot Identification tier as an example, the details are as follows:

1. Operation and maintenance units should establish a routine data comparison mechanism to perform constant comparisons between sensors and nearby regulatory monitoring stations (ideally within 1–2 km), mobile air quality monitoring vehicles, or other equipment meeting the performance metrics of the Pollution Hotspot Identification tier, continuously observing changes in sensor data. It is recommended to perform cluster analysis on sensors daily, weekly, or monthly to screen for suspected equipment anomalies or sensing deviations and, if necessary, conduct field inspection comparisons and calibrations.

2. It is recommended that operation and maintenance teams sample at least 10% of

the total number of maintained sensors every three months for field inspection comparisons, with priority given to abnormal equipment identified through cluster analysis. The evaluated tiered performance metrics must, at a minimum, include Relative Error (Error), the Coefficient of Determination (R^2), and the Linear Regression Slope.

3. Recommended operational procedures for field inspection comparisons are as follows:

   (1) Schedule inspection routes and periods based on the sampled abnormal sensors.

   (2) Before inspection operations, perform quality confirmation for reference instruments (or reference sensors) by placing them at regulatory monitoring stations for 5–7 days of parallel comparison. Verify compliance with the pollution hotspot identification tier requirements; the evaluated performance metrics must at least include Relative Error (Error) and the Coefficient of Determination (R^2). For performance standards corresponding to the pollution hotspot identification tier, please refer to Table 4 in Section 2.2.

   (3) Inspection personnel shall follow the scheduled route, verify the lamp pole number and the ID of the target sensor before mounting, and perform onsite traffic control and set up traffic cones.

   (4) Conduct inspections of the exterior and internal mechanisms of the sensor under review. Perform cleaning for filters, intake channels, sensing chambers, fans, and sensing components. Record the surrounding environmental status and compare it with the status at the time of deployment; photographs and records must be taken during the inspection and cleaning process.

   (5) Power on the reference instrument (or reference sensor) and mount it next to the sensor under review, ensuring the distance is within 1 meter and the intakes are at the same height. Once the parallel comparison setup is complete and sensing data output is stable, begin the comparison; the duration must not be less than 12 hours.

   (6) After the required comparison time is met, retrieve the reference instruments (or reference sensors) in sequence.

(7) After completing multiple inspection batches, the reference instrument (or reference sensor) must be returned to the regulatory monitoring station for 5–7 days of parallel comparison. Results from the inspection batches can only be included in the analysis after confirming compliance with the pollution hotspot identification tier performance metrics. If the reference instrument (or reference sensor) fails to meet the standards during post-inspection parallel comparison at the station, the completed inspection batches are considered invalid, and the procedure must be re-executed.

(8) When the regulatory monitoring station concentration is below 15 μg/m^3 , the absolute bias between the sensor and the station is evaluated in two stages: (a) When the station concentration is 9 μg/m^3, if the sensor's absolute bias compared to the station is 8 μg/m^3, it is judged to meet low-concentration performance metrics; (b) When the station concentration is 10~14 μg/m^3 , if the sensor's absolute bias compared to the station is 5 μg/m^3 , it is judged to meet low-concentration performance metrics.

(9) When the regulatory monitoring station concentration is 15 μg/m^3, the sensor's Relative Error (Error) compared to the station must meet the pollution hotspot identification tier performance metrics. For performance standards corresponding to the pollution hotspot identification tier, please refer to Table 4 in Section 2.2.

4. When sensing data fail to meet the pollution hotspot identification tier performance metrics, adjustments to the sensor calibration mode or necessary repairs should be performed. It is recommended to perform sensing data comparison analysis during special periods (e.g., National Day fireworks) or special air quality events (e.g., fires, sandstorms, or odor/non-odor pollution complaints) after completion of calibration or repairs. This practice helps verify the sensor's measurement performance under scenarios of severe air quality fluctuations and evaluates its data consistency with surrounding sensors to confirm that the calibrated or repaired sensor possesses stable and usable monitoring capabilities.

5.7 Sensor Anomaly Alarm Management

When sensor functions exhibit abnormal conditions or unreasonable phenomena, immediate and appropriate actions should be taken. In addition to following the recommendations in the original equipment manufacturers' (OEM) operation manual, continuous tracking and investigation should be performed to establish complete troubleshooting records, which are integrated into an automated anomaly diagnosis management mechanism. The details are as follows:

1. Screen for abnormal sensors through uploaded data: Based on set conditions (such as error codes, circuit board temperature, numerical anomalies, etc.), screen for sensors suspected of being damaged or abnormal. For example:
   (1) Sensing values exhibit missing values, constant values, negative values, or null values.
   (2) Uploading error codes corresponding to damage states, such as abnormal circuit board temperature, low voltage alarms, etc.
   (3) Sensing values exceed the operating range defined in the sensing component's specification sheet.
2. Reporting sensor anomaly states: Devices can be marked as abnormal based on inspection error codes. Anomaly notifications are pushed via communication software (e.g., Line messaging APP, MMS, e-mail), and an anomaly case report is generated containing detailed information on the flagged sensor to serve as a basis for tracking and managing the incident.
3. Anomaly status confirmation: Preliminary determinations can be made based on inspection error codes to categorize the issue as equipment anomaly, communication network anomaly, or power anomaly. A repair work order is generated, including detailed information on the flagged sensor to serve as a reference for repair actions.
4. Maintenance progress control: Manage progress based on the repair work order. Track and control maintenance progress through records such as dispatch time, progress reports, cause of anomaly, repair items, and completion time.
5. Equipment restoration after maintenance: Record maintenance activities in detail, including the cause of the anomaly, repair items and expenses, and processing

time. Establish complete records to serve as a reference for the automated anomaly diagnosis system.

5.8 Rapid Sensor Troubleshooting and Repair

After initial determination based on inspection error codes to categorize the issue as equipment anomaly, communication network anomaly, or power anomaly, remote reset can be performed first for troubleshooting. If the problem cannot be resolved, onsite repair actions shall then be taken. Details are as follows:

1. Operation and maintenance (O&M) personnel preliminary identify devices in suspected damage or abnormal states based on inspection error codes.
2. For devices in an abnormal state, perform a remote reset and restart, then continue observation. If the abnormality recurs and cannot be resolved, proceed with sensor replacement and repair.
3. Maintenance personnel conduct onsite repair actions:
   (1) Verify onsite whether the system failure is caused by communication network interruption or power interruption. If the power or communication supply is interrupted, contact the relevant O&M units for assistance in restoration and include the incident in anomaly tracking and management.
   (2) Visually inspect the sensor's exterior and internal mechanisms for anomalies. These are often caused by intentional external damage or accidental cutting of power wiring by street lamp maintenance units. Internal mechanism anomalies primarily involve intake port blockages (e.g., dirt, organisms) and battery pack damage.
   (3) If no obvious anomalies are found in the exterior or internal mechanisms, perform a forced local reboot and observe the equipment's recovery status. If the problem persists, proceed with sensor replacement and repair.
   (4) Upon completion of these actions, O&M personnel shall report information such as the cause of the problem and the outcome of the actions in the repair work order to complete the repair process.

5.9 Sensor Replacement and Update

For sensors whose anomalies cannot be resolved after rapid troubleshooting, sensor replacement operations shall be conducted immediately, as described below:

1. Note the sensor replacement and update on the repair work order. The sensing data for that node must explicitly record the time of the equipment replacement.
2. To implement a circular economy, decommissioned sensors should be properly recycled and disposed of. The discarded sensors shall be disassembled to evaluate the recyclability of various components. Functional components should be cleaned, repaired, and reused or repurposed as maintenance spares to extend the product life cycle. Damaged or unrepairable components must be entrusted to legal treatment institutions for recycling and final disposal in accordance with the Waste Disposal Act. Special attention must be paid to the disassembly and separate recycling of lithium batteries; mixing them with general waste is strictly prohibited to prevent fire hazards and environmental pollution.
3. Before replacement, new sensors must meet the requirements of the recommended application tier as defined by the $PM_{2.5}$ sensor performance metrics. Furthermore, to maintain consistency with the sensor cluster in the deployment area, they must pass group colocation verification.
4. The replacement procedure for new sensors follows the same protocol as the sensor deployment and installation process, complying with all relevant regulations for construction and electrical safety. Construction records for the periods before, during, and after the operation must also be completed.

Chapter 6: Post-deployment Audit Operational Rules

Although sensors possess the advantage of high spatiotemporal resolution, their sensing accuracy and precision are influenced by the environment and usage patterns. To effectively analyze sensing data for use as a smart environmental governance tool, it is essential to ensure that sensors continuously maintain data quality aligned with the performance metrics of their intended application. Therefore, in sensor quality management, beyond the self-management of pre-factory performance QC, deployment, and operational management by the Operation and Maintenance (O&M) units, third-party audits by user units after deployment are also critical. The goal is to ensure the application objectives and data quality performance metrics through multi-level quality management. To meet the requirements for the pollution hotspot identification tier, key recommendations for third-party audits, recall testing, and anomaly inspections are provided as follows.

6.1 Third-party Audits

To audit the quality of sensor operation and maintenance, the Ministry of Environment (MOENV) or local environmental protection bureaus conduct sensor sampling through third-party audits. Sampled sensors are selected for parallel comparison at regulatory monitoring stations or compared onsite using reference instruments. It is recommended that third-party audits be conducted periodically (e.g., at least once a year). The number of audited units should be representative, and the audit standards must comply with the performance metrics for the pollution hotspot identification tier. Relevant operational procedures are described as follows:

1. Sampling Plan and Quantity: Sensor selection is conducted via random sampling, stratified sampling, or cluster analysis sampling. It is recommended to audit at least 3% (inclusive) of the total sensors within the jurisdiction.

2. Audit Plans: Options include audits conducted at regulatory monitoring stations or regional field audits using reference instruments. The MOENV or local bureaus may select the appropriate plan based on operational needs.

3. Audit Duration: Parallel comparison is conducted for 2–3 days (48–72 hours). Sensing data are calculated as hourly averages, requiring at least 2 days (inclusive) of comparison data from both the reference instrument and the sensor.

Because actual sensor data quality performance cannot be determined when ambient $PM_{2.5}$ concentrations are low, records where ambient concentrations are below 10 μg/m^3 may be excluded during the audit. It is also recommended to avoid conducting comparison operations during the summer vacation period (July–August annually).

4. Audit Comparison Procedures at Regulatory Monitoring Stations:

(1) For audits at regulatory monitoring stations, the audit schedule must be arranged based on the target sensors before the audit begins. The MOENV Environmental IoT Platform (IoT Platform) must be notified in advance to take the audited sensor data offline to prevent misuse during the process.

(2) The O&M unit shall cooperate with the third-party audit team to disassemble the sensors and transport them to designated regulatory monitoring stations for parallel comparison. Once the comparison is complete, the O&M unit shall reinstall the sensors at their original locations.

(3) For comparisons at the station, the sensor intakes should be as close as possible to the reference instrument while avoiding interference with the air intake of either device. Comparisons involving multiple sensors and one reference instrument simultaneously are permissible.

(4) Each audited sensor undergoes comparison analysis against the regulatory monitoring station. The data compliance rate for Relative Error (Error) between the sensor and the station is recorded as the third-party audit quality result.

(5) Standards for station comparison: When the ambient concentration is ≦15 μg/m^3 the absolute bias between the audited sensor and the station is evaluated in two stages: (1) When the station concentration is ≦9μg/m^3, if the absolute bias is ≦8μg/m^3, it is judged to meet the low-concentration performance metrics. (2) When the station concentration is 10~14μg/m^3, if the absolute bias is 5 μg/m^3, it is judged to meet the low-concentration performance metrics. When ambient concentrations are ＞15 μg/m^3, the Relative Error (Error) must comply with the performance metrics of the Pollution Hotspot Identification tier. For these standards, please refer to Table

4 in Section 2.2.

(6) Upon audit completion, the sensor's response time to water mist is tested to evaluate high-concentration response lag. For sensors with excessive lag (e.g., ＞3minutes), the O&M unit must propose improvement plans for performance and mechanical design.

(7) If recommended requirements are not met, sensor calibration must be completed within a specified timeframe. If the standards still cannot be maintained, sensor replacement and update operations shall be performed.

5. Regional Field Audit Procedures Using Reference Instruments:

(1) Reference instruments primarily include $PM_{2.5}$ instruments that comply with the US EPA Federal Reference Method (FRM), Federal Equivalent Method (FEM), or the MOENV QA/QC standards. Comparison operations can be performed in flat areas with significant airflow turbulence to observe changes and differences between the sensors and reference instruments (or reference sensors) and discuss potential causes.

(2) To ensure data quality of reference instruments, they must be placed at regulatory monitoring stations for 2–3 days (total of 48–72 hours) of parallel comparison both before and after the third-party audit. Verification must confirm compliance with the Pollution Hotspot Identification tier; the evaluated metrics must include Relative Error (Error) and the Coefficient of Determination (R^2). Refer to Table 4 in Section 2.2 for specific standards.

(3) After completing the quality comparison at the station, reference instruments may be mounted on various mobile platforms (e.g., mobile monitoring vans) for regional field audits.

(4) Once the third-party audit area has been selected, the reference instrument shall be installed at the center of the audit area, ensuring that its installation height is the same as that of the sensors under review. Upon completion of the reference instrument setup, each sensor under review is subjected to a comparison analysis against the reference instrument. The data compliance rate for the Relative Error (Error) between the audited sensors and the reference instrument is then compared to serve as the third-party audit data

quality result.

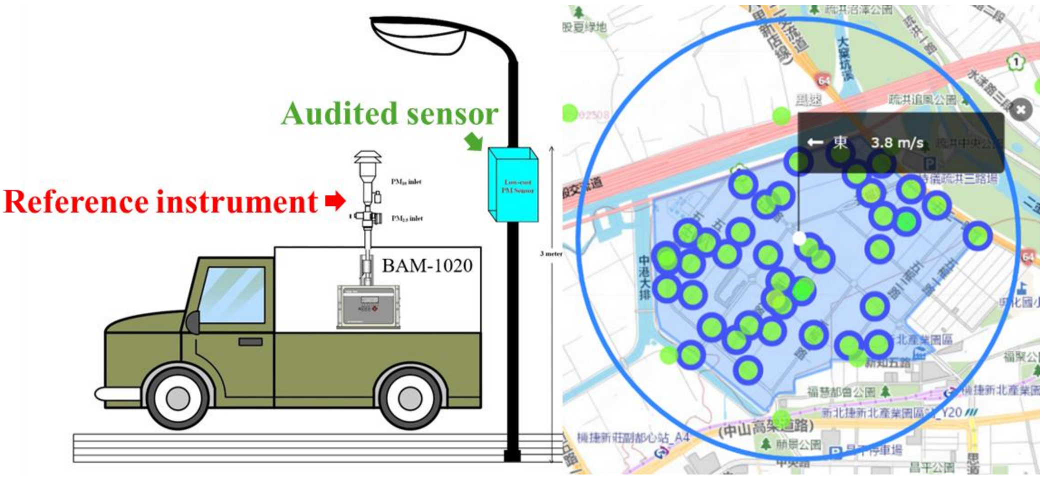

Figure 3. Height and location for reference instrument placement

(5) For regional field audits using reference instruments, each session must last at least 48 hours (inclusive). When reference concentrations are ≦15 μg/m^3, if the absolute bias between the sensor and the reference is ≦8 μg/m^3, it is judged to meet the low-concentration performance metrics. When concentrations are ＞15 μg/m^{3}the Relative Error (Error) between the sensor and the reference must be ≦50%.

(6) If requirements are not met, sensor calibration must be performed within a set period. If standards still cannot be maintained, sensor replacement and update operations shall be executed.

6.2 Recall Testing

To track the performance of sensing equipment that has passed sensor type validation, the Ministry of Environment (MOENV) or local environmental protection bureaus conduct recall testing to evaluate performance variations across different models, batches, or fields. This serves as a reference for improving design, production assembly, equipment installation, and inspection audits.

1. Recall testing procedures are identical to type validation and focus on key testing items, as detailed in Section 3.3.
2. The quantity, frequency, and testing items for recall testing are determined based on the annual requirements of the Ministry of Environment (MOENV) or local environmental protection bureaus.

3. Verification Objective of Recall Testing: To confirm that the internal mechanisms and performance of the recalled sensors comply with the specifications and performance of the originally deployed equipment.
4. Operational Procedures for Recall Testing: Sampling tests are conducted on sensors already deployed and operational in the field. The O&M unit shall assist in disassembling the sensors for the testing unit to take back to the laboratory for recall testing. Upon completion of the tests, the sensors are returned to the O&M unit for restoration.
5. If recall testing reveals that the sensor mechanism differs from the original laboratory test, the O&M unit must remove all sensors of that model and re-execute deployment in accordance with the operational rules of this guide. Data collected from the time of the non-compliance determination until the confirmation of completed improvements shall be considered invalid.
6. If recall testing finds that sensor performance fails to meet the performance metrics for the pollution hotspot identification tier, the O&M unit shall complete repairs and adjustments as quickly as possible and resubmit the sensor for laboratory testing to confirm that the improvement has been completed. Data from the time of the non-compliance determination until the confirmation of the completed improvement are deemed invalid data. The O&M unit shall comprehensively inspect sensors of the same model to prevent similar abnormal states from occurring in that model.

6.3 Anomaly Inspections

The Ministry of Environment (MOENV) or local environmental protection bureaus continuously perform cluster analysis on operational sensors. Based on sensors exhibiting abnormal cluster responses, unscheduled field audit comparisons are conducted to evaluate the drift behavior of suspected abnormal sensors.

1. Anomaly Sensing Screening: Use cluster analysis to screen sensors with differing responses. Evaluate the necessity of field inspection by long-term observation of the temporal characteristics and frequency of anomalies.
2. Reference Instruments (or Reference Sensors) for Anomaly Inspections: Must meet or exceed the application tier performance metrics of the sensor under

review. Alternatively, reference sensors collocated long-term at regulatory monitoring stations may be used for parallel comparison.

3. Parallel Comparison Duration: Observation must last long enough to capture the characteristic repetitive abnormal behavior of the sensor within the cluster. Analyze the consistency of abnormal trends and the Relative Error (Error) between the reference instrument (or reference sensor) and the abnormal sensor to determine whether abnormal high or low values are due to sensor malfunction or environmental events.

4. If an equipment anomaly is determined, follow equipment maintenance procedures; data collected from the time of non-compliance determination until confirmation of completed improvement shall be considered invalid data. If an environmental anomaly is determined, follow environmental law enforcement application procedures.

Chapter 7: Sensing Data Publication Rules

To ensure that the public correctly understands the meaning represented by sensing data, this guide establishes tiers based on the application purposes of the sensors. Among these, sensing data meeting the Level 4 "Supplemental Regulatory Monitoring Station Reference" tier can supplement the regulatory monitoring network data and be directly utilized by the public as reference data for ambient concentrations. Sensing data meeting Level 3 "personal exposure assessment" and Level 2 "pollution hotspot identification" tiers exhibit larger biases; although their trends are highly consistent with ambient concentrations, they are more suitable for creating $PM_{2.5}$ concentration maps using color scales. The resulting sensing data are intended only as a reference to help interpret differences in regional environmental pollution concentrations. Under the Ministry of Environment's (MOENV) goal of promoting public-private collaboration and co-creation based on transparent and open environmental data, sensing data publication rules have been established for sensors that meet the requirements of the pollution hotspot identification tier.

7.1 Real-time Sensing Data Publication Rules

Sensors must meet the pollution hotspot identification tier requirements and strictly implement the operational rules for pre-factory performance QC, deployment, operational management, and post-deployment auditing. Sensing data may be published in real-time provided all of the following requirements are met:

1. The sensor model has passed pre-factory performance QC and complies with the pollution hotspot identification tier performance metrics in both field evaluations and laboratory testing.
2. All sensors have passed colocation prior to deployment. Operational sensors must undergo regular maintenance and periodic inspections and meet the pollution hotspot identification tier performance metrics.
3. Sensors undergo regular degradation analysis and dynamic data calibration. If sensing data fail to maintain the pollution hotspot identification tier performance metrics even after calibration, the sensors must be replaced or updated; data publication may only resume once standards are met.
4. If third-party audits, recall testing, or anomaly inspections reveal non-compliance

with the pollution hotspot identification tier performance metrics, repairs and improvements must be completed within a specified timeframe. Data publication may only resume once standards are met.

7.2 Sensing Annotation Conditions

When the following situations occur, the data will not be published as they are not representative:

1. If sensing data exceeds the maximum concentration used in type validation testing, the numerical value will not be published and will instead be annotated as "exceeding the upper limit".
2. For non-representative data caused by equipment failure, implementation of maintenance and servicing, or inspection and calibration, the numerical value will not be published and will instead be annotated with the equipment status.

7.3 Responsibilities and Obligations for Data Publication

1. The O&M unit is responsible for providing sensing data and implementing the operational rules for pre-factory performance QC, deployment, and operational management. In addition to performing autonomous periodic maintenance and inspections, the unit shall maintain the sensing data's compliance with the pollution hotspot identification tier performance metrics through data degradation analysis and dynamic data calibration.
2. Upon verification by the local environmental protection bureau of the O&M unit's records and results regarding periodic maintenance and inspections, sensor degradation analysis, and dynamic data calibration—and, if necessary, through post-deployment audits—to confirm that the sensors meet the pollution hotspot identification tier performance metrics, their sensing data may be published in real-time.

Chapter 8: Data Center and Application Analysis Platform

To effectively utilize the operational efficiency of the air quality sensing IoT, control and audit requirements are established for pre-factory performance QC, deployment, operational management, and post-deployment audit operations to ensure that sensors provide representative sensing data that meet quality standards. Through the collection, cleaning, and analysis by the data center (MOENV IoT Platform), the operational status of each sensor is managed to perform equipment anomaly alarming, data management, and data warehousing, enabling managers to grasp the data reception status in real-time. The collected sensing data are presented on maps showing sensing distribution, meteorological data, and environmental information through the sensing data analysis platform (MOENV WoT Platform). At the same time, it provides data analysis tools to resolve pollution hotspots, pollution timing, and suspicious regulated factories in areas of concern.

8.1 MOENV IoT Platform

The IoT Platform (referred to as the IoT Platform) is the data center of the Ministry of Environment (MOENV), which collects data from regulatory monitoring stations, smart city/township air quality sensors (jointly deployed by central and local governments), and campus air quality sensors. Among these, the smart city/township air quality sensors primarily sense $PM_{2.5}$, temperature, and relative humidity, with data uploaded at a frequency of one record every 1 to 3 minutes. The data center provides data quality checking and cleaning functions, including inspections for anomalies such as negative values, constant values, and duplicated time values. Statistical tables for equipment with data anomalies are provided to local environmental protection bureaus and O&M vendors. Furthermore, data from problematic equipment are taken offline to establish sensor lifecycle management and prevent erroneous data from being cited by external parties.

8.1.1 Sensor Equipment Management Interface

The IoT Platform provides a sensor equipment status dashboard, offering administrators operational status analysis for individual sensors and project-based sensors through an intuitive graphical management interface (as shown in Figure 4). It allows real-time tracking of the completeness rate of sensing data reception, enabling administrators to be promptly informed of sensor equipment anomalies for immediate maintenance and troubleshooting.

Figure 4. IoT Platform Real-time Data Transmission Monitoring Dashboard

8.1.2 Equipment Status Checking

After the data uploaded by the sensing equipment are imported into the IoT Platform, they are inspected according to various verification rules set by the platform. If numerical anomalies are detected, the system will directly flag the abnormal devices. Currently, for the anomaly monitoring of devices, the platform uses each sensing device as a unit to perform inspections for four types of states: null values, negative values, constant values, and duplicated minute values. These inspections can be conducted through scheduled programs or real-time verification to faithfully reflect the potential status of the devices.

Table 5. Sensor Anomaly States

Anomaly Value	Measured Item	Definition	Program Processing Logic
Duplicated Minute	pm2_5, humidity, temperature	More than one record for the same measured item within a minute	Deduct redundant records; excluded from completeness rate calculation (users cannot download duplicated values)
Null Value	pm2_5, humidity, temperature	The value is empty No measurement recorded	Deduct records with "empty strings, spaces, or non-numeric values"; excluded from completeness rate calculation (users cannot download null values)
Negative Value	pm2_5, humidity, temperature	The value is negative	Deduct records with values less than 0; excluded from completeness rate calculation
Constant Value	pm2_5	Values remain identical for 12 consecutive hours	Deduct records where values are identical for 12 consecutive hours; excluded from completeness rate calculation

8.1.3 Equipment Anomaly Handling Process

When the system identifies an anomaly in a sensing device through verification rules, it provides a statistical table for the operation and maintenance (O&M) unit to conduct verification.

專...	PM2_5定值筆數	PM2_5負值筆...	PM2_5時間重複值...	PM2_5空值	humidity_零值筆數	humidity_負值筆...	humidity_時間重複...	humidity_空值
25	44262	0	1	0	0	0	1	0
12	45037	0	49391	0	1940118	0	49391	0
18	0	0	7838	0	291511	0	7832	0
19	91170	0	155762	0	2569535	0	155742	0
20	391272	0	105648	0	4401438	0	105168	0
2	37295	0	65888	0	4683841	0	65888	0
21	349017	0	55662	0	543388	0	55124	0
7	10950	0	53982	0	85969	0	53982	0
22	0	0	220388	0	7770098	0	220388	0
3	52408	0	23097	0	410625	0	23097	0
17	61801	0	1275600	0	0	0	1275600	0
10	0	0	52919	0	49972	0	52888	0
11	0	0	40020	0	17918	0	40020	0

Figure 5. Equipment Anomaly Statistical Table

8.2 MOENV WoT Platform

8.2.1 Data Presentation Interface

The WoT Platform is the application analysis platform of the Ministry of Environment (MOENV), established to meet the needs for integrated display of sensing application analysis and air quality-related meteorological data, and to enhance the functions for auxiliary environmental protection inspections. Through visualization and spatial mapping, it filters data usable for pollution investigation and handling operations. It also integrates and analyzes value-added data from external units and environmental quality data to provide accurate interpretation of air quality change trends and display high-resolution air quality spatiotemporal maps. By linking air quality data with pollution source hotspot analysis data, it visually presents pollution potential hotspot maps to assist operational needs in understanding pollution trends and tracing pollution hotspots. Simultaneously, it plans a cross-unit environmental sensing information query and sharing mechanism. The user interface is shown in detail in Figure 6. The system will be available for use by central and local governments to assist in the tracking and investigation of pollution sources, while supporting internal decision-making analysis applications and strengthening environmental governance and smart inspection capabilities.

Figure 6. MOENV WoT Platform Presentation Interface

8.2.2 Sensing Data Analysis Technology

The WoT Platform aggregates environmental data such as fine particulate matter ($PM_{2.5}$), volatile organic compounds (VOCs), temperature, and relative humidity from the IoT Platform, monitoring them on a minute-by-minute basis. Through an environmental data analysis operating environment with high availability, high performance, and high computing power, the platform has developed "Artificial Intelligence Air Pollution Potential Hotspot Analysis" technology. It provides primary analytical services such as "pollution potential location analysis," "automatic air pollution event analysis," and "air pollution footprint reconstruction maps" (as shown in Figure 7). The system automatically performs air pollution estimation and alerting. Through real-time message (Line Messaging APP) notifications, it enables inspection personnel to shift from passive participation and one-sided reception of report results to taking proactive initiatives, investigating and handling pollution more efficiently.

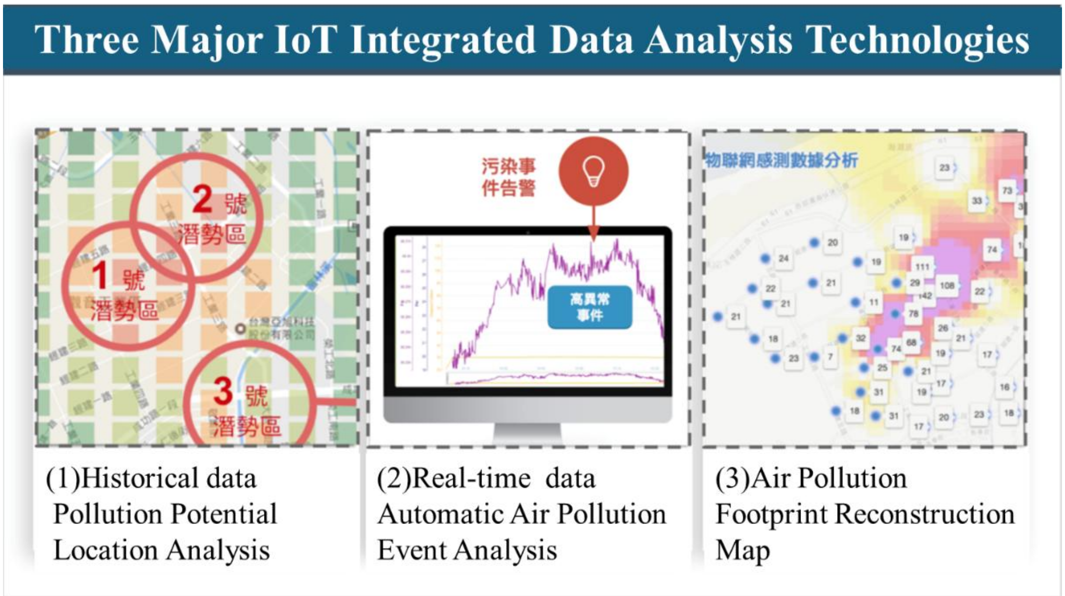

Figure 7. Three Major IoT Integrated Data Analysis Technologies

1. Pollution Event Determination: Pollution alarm event analysis identifies anomalies based on temporal anomalies (e.g., a single sensor value greater than 2.7 times the standard deviation within 1 hour), spatial anomalies (e.g., a single sensor value in an area greater than 2.7 times the standard deviation of other sensors' data), and data anomalies (e.g., values greater than 45 μg/m^3).

   (1) High Pollution Event: The number of relative anomalies exceeds 20, the duration exceeds 20 minutes, and 4 or more sensors within 1 km exhibit anomalies; $PM_{2.5}$ sensing values of 45 μg/m^3 or below (inclusive) are excluded.

   (2) Medium Pollution Event: The number of relative anomalies exceeds 15, the duration exceeds 15 minutes, and 4 or more sensors within 1 km exhibit anomalies; $PM_{2.5}$ sensing values of 45 μg/m^3 or below (inclusive) are excluded.

   (3) Low Pollution Event: The number of relative anomalies exceeds 10, and the duration exceeds 10 minutes; $PM_{2.5}$ sensing values of 45 μg/m^{3}or below (inclusive) are excluded.

   (4) Sudden Event (e.g., Fire Event): Recorded behavior where neighboring air quality sensors sequentially respond with high values within a continuous timeframe is treated as a single sudden event, which must meet one of the following conditions:

A. Meets the criteria for a high pollution event, the event duration exceeds 60 minutes (inclusive), and for more than 30% of the event time, $PM_{2.5}$sensing values exceed 90 μg/m^3 (inclusive), simulating a persistent pollution scenario (such as a smoldering state after a fire).

B. Meets the criteria for a low pollution event, and the maximum $PM_{2.5}$ sensing value exceeds 200 μg/m^3 (inclusive), simulating a sudden air pollution event that occurs rapidly within a short period (such as the initial stage of a fire).

2. Pollution Potential Location Analysis: This primarily utilizes the characteristics of sensor cluster analysis combined with information such as regional wind direction and wind speed. When concentration trends change from upwind to downwind, weighted calculations of pollution events and environmental wind direction are used to perform pollution potential hotspot analysis. Currently, pollution potential hotspots for each city and county are automatically generated weekly and provided to local environmental protection bureaus for reference.

3. Automatic Air Pollution Event Analysis: This primarily utilizes artificial intelligence for spatiotemporal sequence anomaly (time-series analysis) detection models. When abnormal features appear at specific times and locations, they are automatically interpreted as anomalies, and alarm notifications are enabled.

4. Air Pollution Footprint Reconstruction Map: This primarily records and presents the spatiotemporal characteristics of the aforementioned pollution concentrations through geographic information visualization, allowing for repeated playback. It provides local environmental protection bureaus with references for the locations where air pollution footprints appear. Combined with the characteristics of factory declarations or emission data in that area, it can be used to decide whether to initiate inspection operations.

8.2.3 Auxiliary Smart Inspection Functions

1. Pollution Event Retrospection and Alerting: The WoT Platform provides real-time 72-hour sensing data playback and an alert event list function. Through the operation of the timeline, users can further understand short-term air quality

change trends. The alert event list allows for an understanding of the temporal and spatial status of each event. Furthermore, it integrates and displays public complaint data (as shown in Figure 8) to simultaneously grasp public needs and effectively resolve pollution incidents.

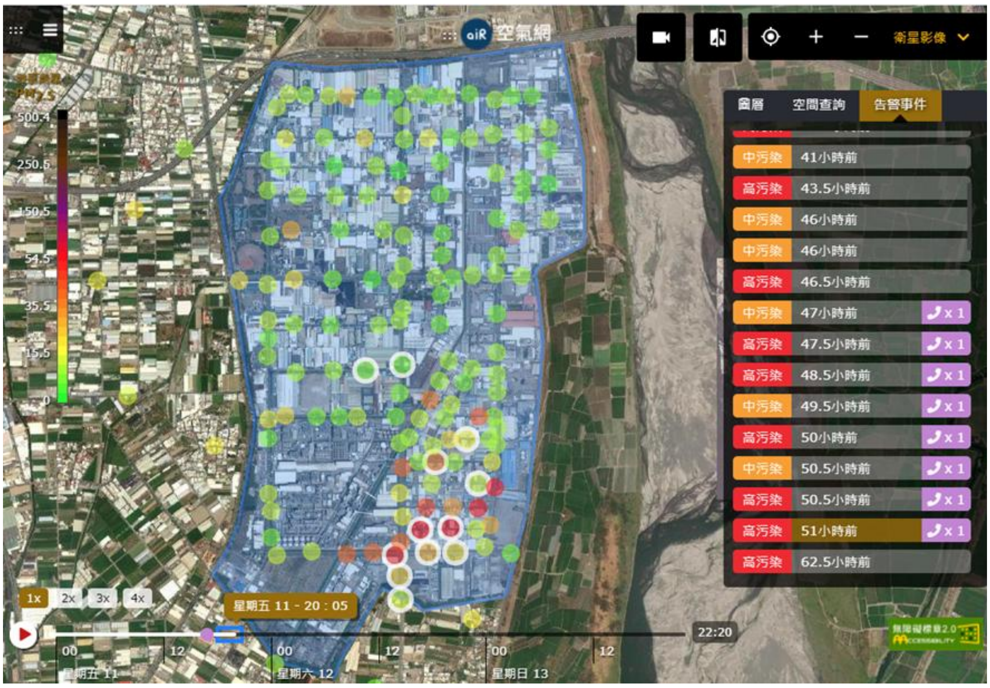

Figure 8. Pollution Event Alerting and Retrospection

2. Three-Stage, Six-Step Smart Inspection: The WoT Platform narrows down the range based on hotspots, verifies abnormal events, analyzes time periods, cross-checks factories, and locks onto sensing points around factories. Finally, it combines technological instruments to conduct smart inspections, evolving into the advanced "Six Steps of Air Pollution Smart Inspection" (as shown in Figure 9). Through the Environmental Sensing IoT, indicators such as pollution hotspots are identified to combat pollution crimes and recover illegal assets. Sensing data analysis also performs actual verification and emergency early warning functions in industrial safety incidents (fires, explosions), open-air burning incidents, and public complaint cases.

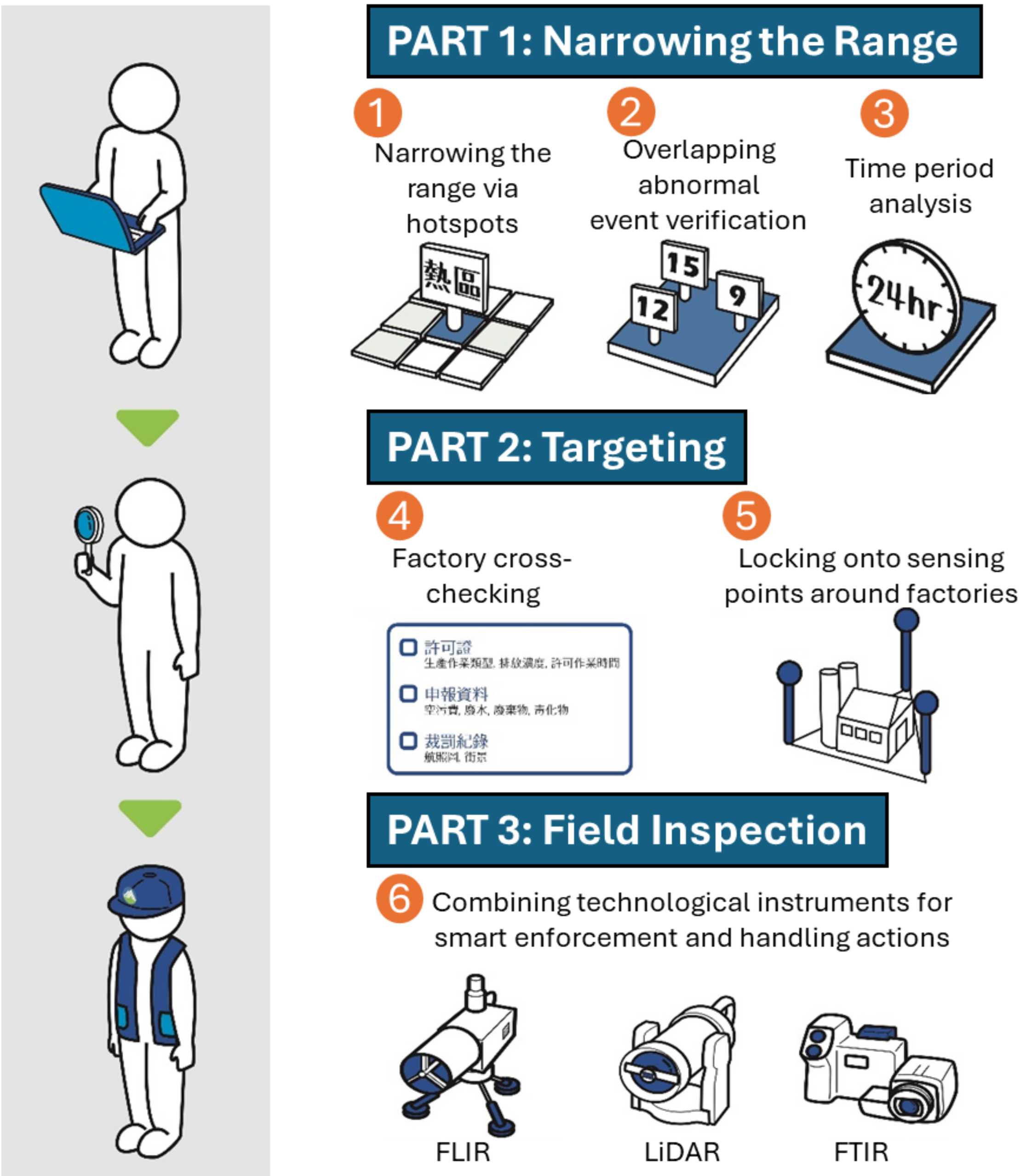

Figure 9. Three Stages and Six Steps of IoT-Assisted Environmental Protection Inspection

3. Auxiliary Inspections Application Interface: The WoT Platform precisely manages all historical data. Through big data processing and artificial intelligence, it effectively implements four steps of the inspection process: narrowing the range via hotspots, overlapping abnormal event verification, time period analysis, and locking onto sensing points around factories. The pollution potential map summarizes suspicious areas by analyzing sensing data, wind direction, and wind speed. It further generates pollution heatmaps by

overlapping abnormal events. Finally, a time period analysis is effectively conducted through abnormal event and sensing data calendar charts. The integration of relevant information assists in the spatiotemporal information integration for planned inspections, achieving range narrowing.

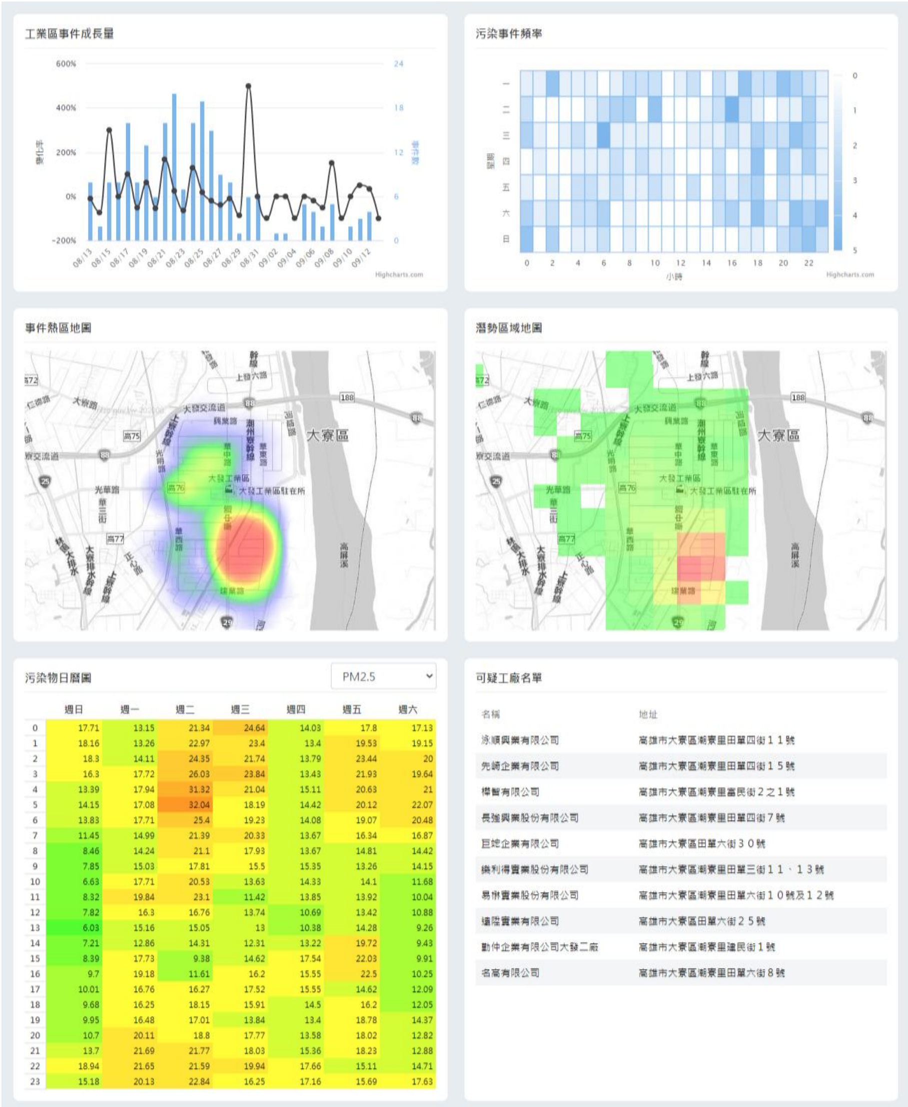

Figure 10. WoT Platform Auxiliary Inspection Tool Interface

4. In-depth Inspection Analysis Interface: After initially completing range narrowing using the WoT Platform, the environmental sensing data application auxiliary system can be used to lock onto sensing points around factories. This system provides users with the function to flexibly select sensors in a bounding box and integrates sensing values, abnormal events, and meteorological data for comprehensive weekly analysis. It offers users more detailed range-narrowing functions to achieve target locking in the six major processes.

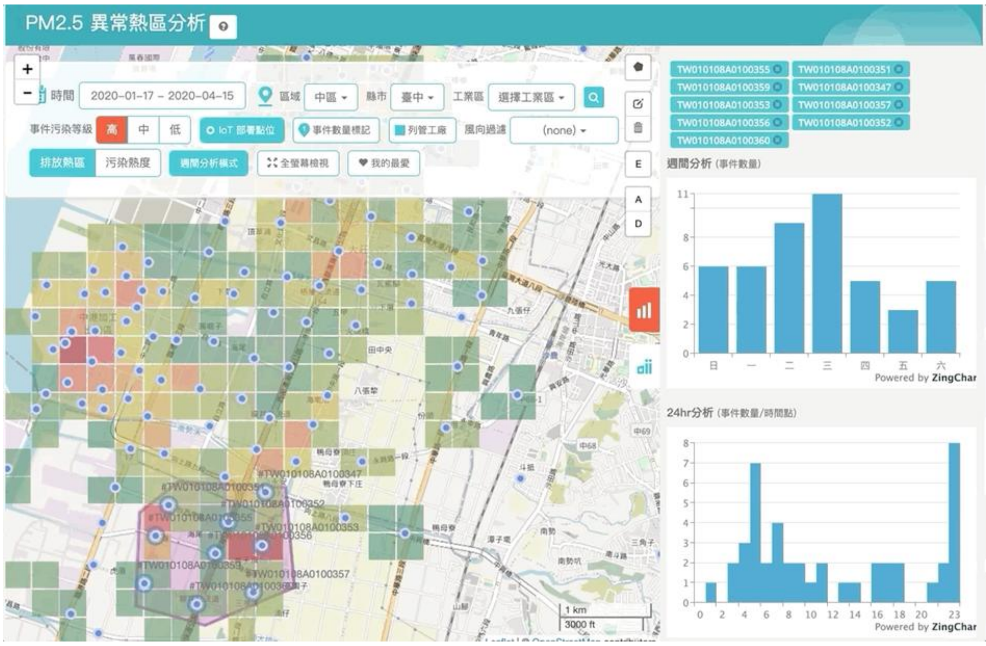

Figure 11. In-depth Inspection Analysis Interface ($PM_{2.5}$)

5. Given that odor pollution accounts for a significant proportion of complaint cases, sensors jointly managed by central and local governments utilize additional Volatile Organic Compound (VOCs) sensing components. Sensing data is simultaneously transmitted back to the MOENV IoT Platform. After VOCs values are converted by algorithms, red dots represent sensors with higher relative abnormal values. At the same time, the sensor location and its weekly, 24-hour, and wind direction analysis within the time period are available, strengthening the precision of range narrowing.

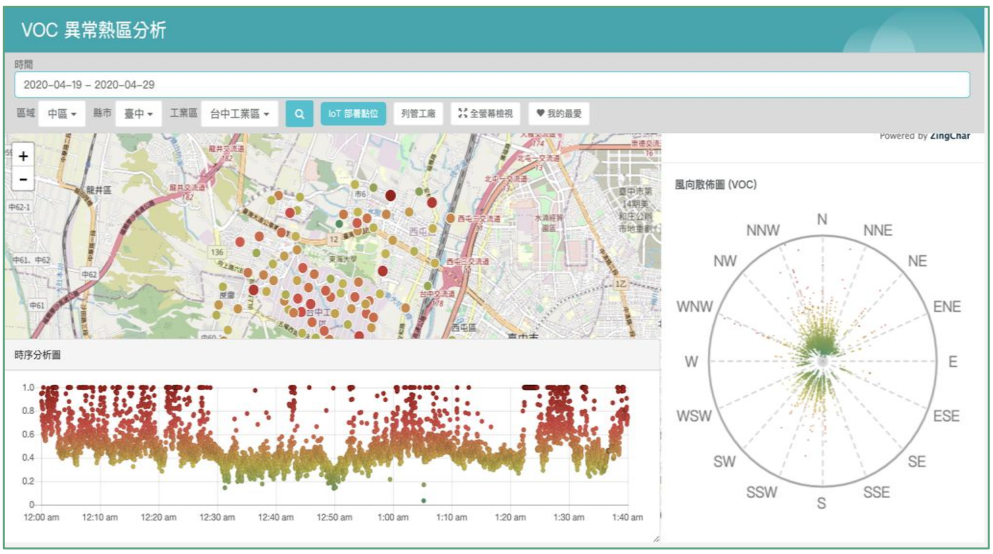

Figure 12. In-depth Inspection Analysis Interface (VOCs)

6. Auxiliary Environmental Protection Inspection: By utilizing information provided by the WoT Platform, such as pollutant types, pollution hotspots, and time periods, data collection and comparison are conducted for suspicious targets. Examples include verifying permit status and contents, comparing declaration data, and reviewing inspection and citation records. These actions help screen for suspicious industries and operators. This is then supplemented by scientific instruments such as Infrared Thermography (FLIR), 3D LiDAR, and Fourier Transform Infrared Spectroscopy (FTIR). After scientific evidence collection, the analysis results are used to formulate inspection and investigation projects to execute environmental law enforcement.

Chapter 9: Sensing Data Application Analysis

Sensors with high spatiotemporal resolution have the primary advantage of observing air quality changes in microenvironments. By analyzing the variation behavior of sensors in temporal and spatial dimensions and the correlation between sensor clusters and meteorological conditions, the spatiotemporal trajectories of pollution events can be effectively resolved. Joining Environmental IoT alarm groups enables effective monitoring of real-time conditions in areas of concern. When high-pollution alert events occur, the alarm group will immediately push messages including sensing information, meteorological data, and information on nearby regulated factories. Upon receiving these messages, if the location is within the aforementioned areas of concern or public complaint hotspots, inspection personnel can be quickly dispatched to the site to verify the situation and report findings back to the alarm group, ensuring control over abnormal areas and addressing public complaint issues. This approach has achieved significant results for air quality applications related to environmental governance, smart enforcement, sudden events, and weather system impacts. The following sections briefly describe the methods for each application analysis.

9.1 Industrial Area Hotspot Analysis Aiding Smart Enforcement

By utilizing data from sensors deployed in industrial areas and surrounding communities, and analyzing the temporal variation behavior of sensors along with the spatial variation characteristics of sensor clusters in comparison with meteorological conditions, the hotspots of pollution sources can be narrowed down. By analyzing the temporal changes in pollution hotspots, the time cycles of pollution behavior can be categorized, and pollution characteristics can be identified (as detailed in Figure 13). The MOENV has established the entire AI hotspot analysis function within the WoT Platform, providing environmental protection inspection units with technological tools to assist in smart enforcement.

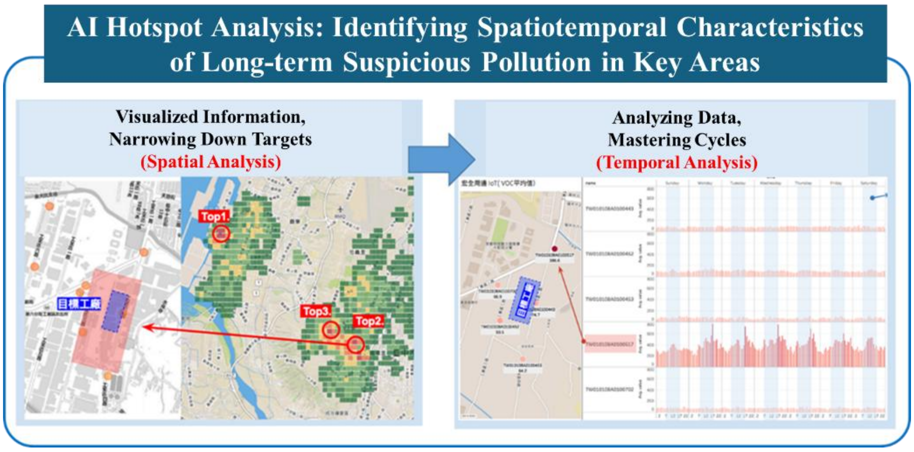

Figure 13. Understanding Pollution Characteristics Through AI Hotspot Analysis of Sensing Data

Previously, the inspection process of environmental protection inspection units consisted of three major stages. Stage 1, preliminary inspection, was based on established schedules or cases reported by the public, involving data cross-checking and onsite patrols for specific targets. Stage 2, in-depth inspection, targeted suspicious entities identified during the preliminary stage for intensive monitoring, confirming the characteristics of illegal emission behaviors, collecting specific evidence, formulating onsite inspection plans, and coordinating with prosecutors and police units to combat illegal activities. Stage 3 involved collaborative operations among prosecutors, police, and environmental authorities to raid illegal emission sites, cite malicious factories onsite, and obtain direct evidence of illegal activities.

With the support of the Air Quality Sensing IoT in assisting environmental inspections, pollution hotspot analysis of sensing data helps inspection units focus on areas with high-pollution sources. It further aids these units by performing in-depth analysis of emission behavior characteristics via sensors around suspicious factories, assisting in identifying illegal targets. By providing effective supporting information around the clock, it reduces the workload of inspection personnel and achieves the efficiency of auxiliary smart environmental law enforcement. By utilizing the Environmental Sensing IoT to identify indicators such as pollution hotspots, pollution crimes are combated and illegal gains are recovered, effectively validating the practical functions of IoT technological tools (as detailed in Figure 14).

Figure 14. Validating Sensors Aiding Smart Environmental Law Enforcement

9.2 Sensors Aiding in Clarifying Cross-Regional Pollution Sources

Regulatory monitoring stations are primarily used to assess large-scale air quality conditions. Due to limitations in their installation height and surrounding obstructions, it is relatively difficult for them to directly reflect the immediate impacts of local pollution sources. In the past, when regulatory monitoring stations recorded abnormally high concentrations that were inconsistent with prevailing weather conditions, it was often challenging to promptly clarify the underlying mechanisms and pollution sources. With the gradual establishment of the Air Quality Sensing IoT, using regulatory monitoring stations as analysis nodes combined with the surrounding densely distributed air quality sensors allows for the use of high spatiotemporal resolution data to help understand the temporal and spatial trajectories of pollution generation and dispersion, thereby assisting in clarifying cross-regional pollution sources.

Taking March 8, 2020, as an example, at 20:00 on that day, the Puzi station recorded a $PM_{2.5}$ concentration of 51 μg/m³, showing an abnormally high value. Subsequently, at 23:00, the Annan and Tainan stations also recorded $PM_{2.5}$ concentrations as high as 67 μg/m³ and 78 μg/m³, respectively. Further cross-comparison with the Air Quality Sensing IoT data revealed that the pollution signal was gradually transmitted from the north of the Puzi station to the south. After verification with the Yunlin County Fire Bureau, it was confirmed that a fire had occurred at a feed factory in Wanxing Village, Shulin Township, Yunlin County at 19:00 that day. Aided by the wind, the smoke dispersed southward, ultimately affecting the air quality in the Chiayi and Tainan areas (as detailed in Figure 15).

Based on the above cases, it is evident that when performing regional air quality analysis through sensing data, a multi-layered sensor subset approach can be adopted with regulatory monitoring stations as the core, extending from nearest to farthest. This approach combines geographic conditions (such as intra-regional or cross-regional), human factors (such as stationary or mobile pollution sources), and meteorological conditions (such as wind speed and direction) to analyze the pollution change trends across different sensor subsets and identify pollution sources. This method not only compensates for monitoring blind spots in the spatial coverage of regulatory monitoring stations but also helps determine whether high values at regulatory monitoring stations are due to equipment or environmental factors, while validating the application capability of the Air Quality Sensing IoT in pollution source tracing.

Furthermore, to enhance the resolution capability for cross-regional pollution events, it is recommended to introduce meteorological numerical models (such as WRF, Weather Research and Forecasting Model) for analysis. This is particularly important during "stagnant weather" with weak wind speeds and poor atmospheric dispersion conditions, where local circulation (such as sea-land breeze switching and mountain-valley wind effects) has a critical impact on the accumulation and transport of pollutants. By coupling high-density sensing data with meteorological models, the precision in resolving fine-scale spatial wind fields and pollution variations can be significantly strengthened. This assists in determining whether pollution sources are from long-range transboundary transport, cross-regional transport from neighboring counties and cities, or local emission accumulation, thereby optimizing the accuracy of regional air quality management and emergency response decision-making.

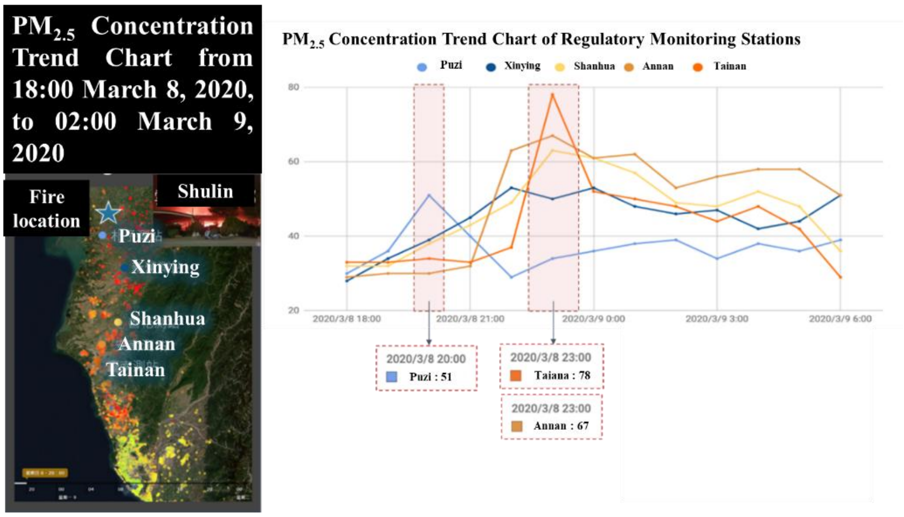

Figure 15. Sensors Aiding in Tracing Abnormally High Values at Regulatory Monitoring Stations

9.3 Sensing Data Aiding in Sudden Environmental Event Analysis

In addition to emissions from stationary and mobile pollution sources, human factors contributing to poor air quality include fires or chemical leak accidents. The range and impact duration of such sudden pollution events have a significant impact on the environment. Sensing data possesses real-time identification capabilities for understanding sudden environmental anomaly events and can analyze the pollution transmission behavior within a city/county, across cities/counties, or regarding domestic and transboundary pollution.

1. Source Tracing Analysis of Abnormal Events: Starting from the push notification of a pollution event by regional sensors, the combination of big data analysis and meteorological data can clearly display the movement trajectory of an abnormal environmental event. Through the pollution footprint retrospection function, the approximate starting point of the pollution event can be predicted. Upon verification with fire rescue units or environmental accident emergency response systems, the disaster accident points and pollutant types can be effectively linked to the temporal and spatial correlation of the sensing data.

2. Impact Range Analysis: Based on the development of the abnormal event, sensors provide air pollution data for the local microenvironments. According to regional wind direction and speed, combined with changes in the concentration of sensing data, spatial pollution gradients can be mapped. Through the push function of pollution alerts, real-time environmental information is provided to rescue units or local residents. The movement and evolution of the polluted area can also be estimated and warned against using meteorological forecast information.

3. Impact Time Analysis: Under continuous collection of sensing information, the impact time of the pollution event on the microenvironment can be estimated through the trends in environmental sensing concentrations and information on rescue progress at the disaster site, combined with meteorological data calculations. In addition to providing warnings for autonomous health protection

to residents within the polluted range, it also provides a reference for rescue units to evaluate emergency response measures and the execution of evacuation plans in high-pollution areas.

Figure 16. Sensing Data Aiding in Sudden Environmental Event Analysis

9.4 Sensing Data Aiding in Response to Public Complaints

Due to their small size, low cost, and ease of installation, sensors can be appropriately disguised to perform full-time monitoring of specific areas of concern or public complaint hotspots. Previously, regarding odor events reported by the public, environmental protection units would dispatch inspection personnel with equipment to conduct onsite measurement and sampling upon receiving reports. However, this often missed the spatiotemporal conditions of high-concentration pollution, resulting in ineffective resource investment by inspection units and an inability to provide effective responses to public complaints. Current recommended practices for such events involve deploying temporary sensors in complaint areas. By pre-evaluating suspicious pollution sources around the complaint area and analyzing the prevailing wind direction and speed during events, suitable sensing points can be planned for mobile deployment. Utilizing correlation analysis of temporal, spatial, and meteorological conditions, the placement of temporary sensors is continuously adjusted. Combining data analysis with other high-end instruments can effectively narrow down suspicious factories, reduce inspection manpower, and provide concrete responses that address public concerns.

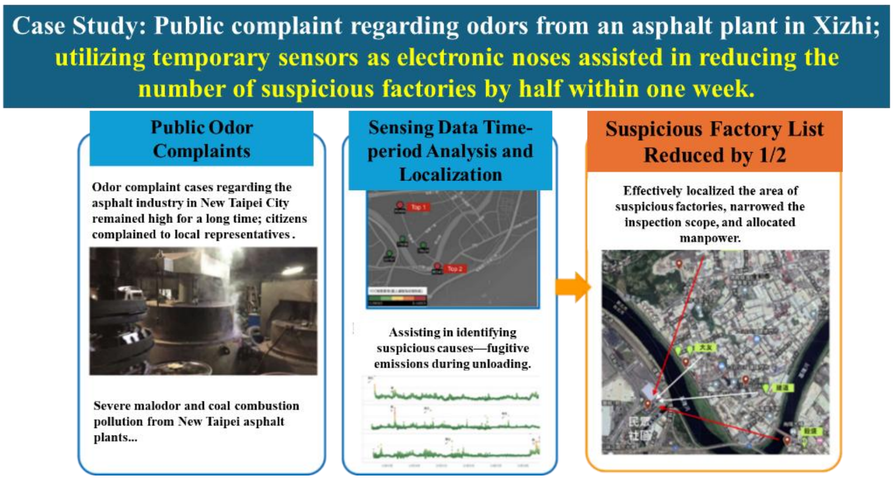

Figure 17. Sensing Data Aiding in Response to Public Complaints

9.5 Sensing Data Aiding in Understanding Sudden Accidental Events

The Air Quality Sensing IoT performs data analysis within established sensing missions, providing round-the-clock air quality information for sensing areas. In addition to $PM_{2.5}$, analyzed sensing information can simultaneously include VOCs data to assist in identifying pollutant types and abnormal signs. Taking a case occurring on Zhonghua Road, Miaoli City on March 12, 2020, as an example, the local environmental protection bureau had deployed air quality sensors for long-term data analysis to monitor the emission behaviors of regulated factories. Since VOCs sensing data consistently showed sudden high values a week before the incident. To clarify the cause of these high values, inspection personnel were dispatched that day carrying a FID (Flame Ionization Detector) to patrol surrounding factories and conduct site surveys specifically at sensing points where high VOCs values were detected. Upon arrival, inspectors detected a gas odor, and FID monitoring showed 21.9 ppm in the ambient air. After searching for the source and measuring a manhole cover, the reading reached the instrument's upper limit of 10,000 ppm, leading to an immediate notification to the Fire Bureau for assistance. The fire department used a four-gas detector and found flammable gas levels reached 99%, and they immediately sprayed water to lower the temperature. After contacting Chinese Petroleum Corporation (CPC) to confirm the presence of gas pipelines beneath the accident area, CPC closed the pipeline, and the fire bureau dispatched trucks for security. CPC engineers then excavated the road to find the leak point and perform emergency repairs, successfully preventing a potential gas explosion. This once again validated the early warning and protection functions of the Air Quality Sensing IoT for regional public safety.

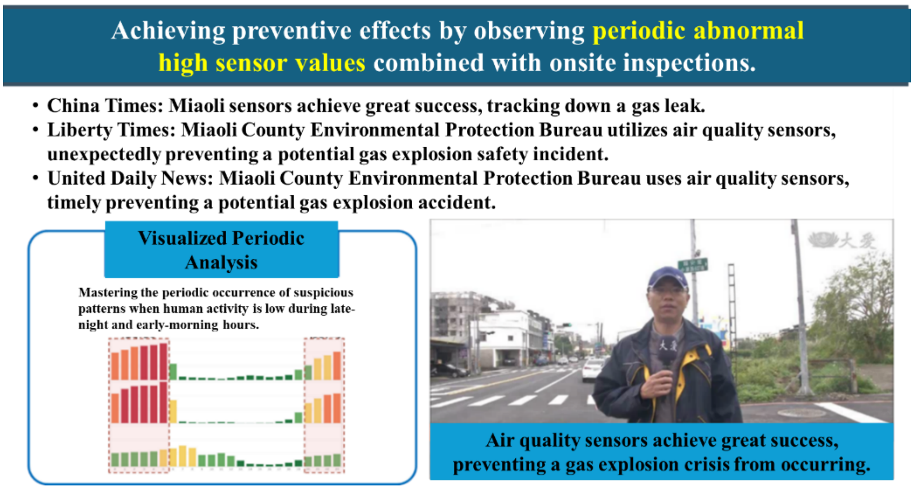

Figure 18. Aiding in Understanding Sudden Accidental Events

9.6 Sensors Aiding in Understanding the Impact of Large-scale Weather Systems on Air Quality

Pollutants in the air often move with the wind. Higher wind speeds can carry away more pollutants, while lower wind speeds make it easier for pollutants to remain in place, affecting local air quality. In addition to the influence of wind speed, the blockage by terrain and winds from different directions are closely related to the transport of pollutants. For instance, even with the same northeast wind, wind field variations differ between the windward side and the leeward side. In Taiwan, which possesses complex terrain, prevailing winds blow in different directions across various seasons, which in turn affects air quality variations throughout the island. The real-time data variations from sensors faithfully present the pollution phenomena caused by weather systems and terrain.

Taking meteorological conditions and regions prone to high $PM_{2.5}$ concentration events as examples, analysis of historical monitoring data shows that poor air quality patterns with $PM_{2.5}$ reaching AQI 100 or above primarily consist of three types: high-pressure impact (Northeast monsoon), high-pressure return flow, and weak synoptic weather patterns. Their atmospheric dispersion conditions are affected by terrain, and the scope of impact varies under different weather patterns. During autumn and winter, when the Northeast monsoon blows under high-pressure influence, the southern region—located in the weak-wind wake area of the monsoon—is more susceptible to high pollution events. When a high-pressure system moves out to sea and transitions to a return flow, the large-scale wind field gradually shifts to easterly winds, causing the central and southern regions to be on the leeward side. This results in lower average wind speeds and less rainfall, which is unfavorable for pollutant dispersion and deposition (as detailed in Figure 19). The third type is the weak synoptic weather pattern. As it is not influenced by large-scale weather systems, the increase in pollutant concentrations primarily stems from local emissions and accumulation. In this pattern, the wind fields across various regions of Taiwan are dominated by sea-land breeze circulation. Locally emitted pollutants undergo regional transport within the western half of the island under the influence of sea-land breezes, leading to persistent accumulation in western areas. Due to unfavorable dispersion conditions, high pollution events are more likely to occur.

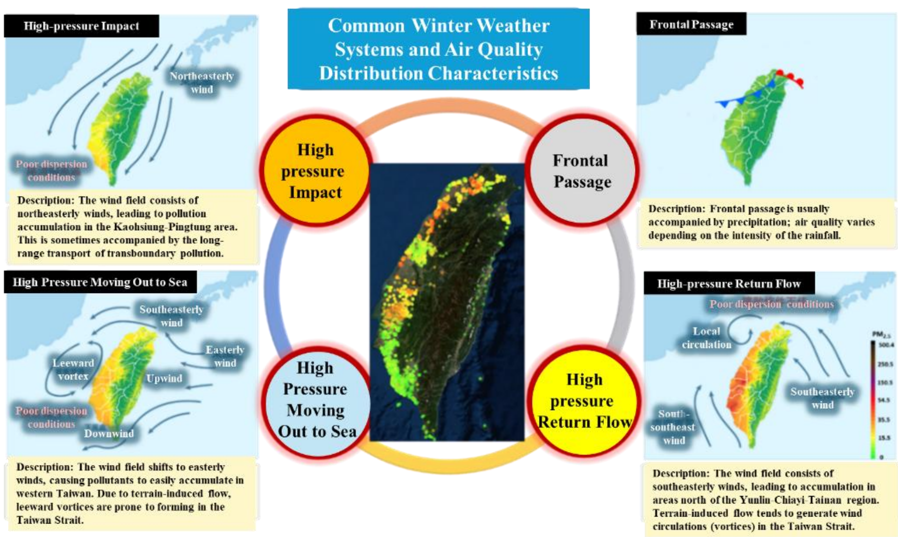

Figure 19. Sensors Aiding in Understanding the Behavior of Winter Weather Systems Affecting Air Quality

9.7 Sensing Data Aiding in Emergency Response Measures for Heavy Air Pollution Episodes

While various factors influence air quality variations, the spatiotemporal distribution characteristics of poor air quality can be identified through sensing data analysis. Taking Taiwan as an example, large-scale high-pollution event days often occur during specific weather patterns, driven by the synergy of weather systems, atmospheric dispersion effects, and topographic conditions, combined with the cumulative impact of both transboundary pollutants and various local emission sources.

To address the autumn and winter air pollution season, the MOENV utilizes air quality forecast analysis to provide guidance on key emergency response tasks for regional and local environmental protection bureaus. It plans emergency response measures and identifies inspection targets, incorporating mandatory, flexible, reward-based, and incentive-based strategies. Through collaborative defense, proactive timing, proactive deployment, pre-planning, rigorous execution, and rolling adjustments, central and local environmental authorities collaborate to resolve air quality issues during the autumn and winter.

Utilizing long-term data from the Air Quality Sensing IoT, potential pollution hotspots during heavy air pollution episodes are analyzed and included as priority inspection targets for local environmental bureaus. Simultaneously, by cross-referencing Pollutant Release and Transfer Register (PRTR) and Continuous Emission Monitoring Systems (CEMS) data, targets for prioritized emission reduction and load reduction are evaluated. By integrating enhanced high-pollution weather forecasting with micro-environment hotspot analysis, the effectiveness of measures taken for air pollution episodes and emission reductions can be assessed and adjusted, progressively achieving the goal of smart environmental management.

Chapter 10: Advanced Implementations of Sensor Technology

Deployment of stationary $PM_{2.5}$ sensors has extensively been promoted for many years now. By accumulating large volumes of $PM_{2.5}$ data with high spatiotemporal resolution, the air quality of areas such as industrial zones, communities, or traffic hotspots can be effectively managed, compensating for information gaps where regulatory monitoring stations are absent. This has become an important basis for local environmental protection bureaus to perform inspections, pollution source tracing, and risk management. As sensor technology matures, sensing applications can expand from stationary forms to being mounted on various mobile carriers, providing mobile sensing services and developing more diverse application scenarios. In the application of air quality forecasting and simulation, sensors provide a large amount of $PM_{2.5}$ data, which, when combined with existing satellite observations, atmospheric chemical transport models (CTM), and AI calibration techniques, improves the spatial resolution of models and enhances the forecasting capability for short-term variations and sudden emissions.

10.1 Mobile Sensor Applications

Stationary $PM_{2.5}$ sensors can monitor small-scale environmental pollution at any time. Through large volumes of data accumulated from long-term continuous measurement combined with big data analysis techniques, pollution variations across different regions in time and space can be effectively resolved, assisting local environmental protection bureaus in understanding pollution trends and serving as an important basis for monitoring stationary pollution sources (e.g., industrial zones, science parks) and suspected illegal emission behaviors. However, limited by the convenience of obtaining consent for land and power usage and insufficient deployment or maintenance funds, existing stationary sensors still find it difficult to fully cover the actual living and activity range of the public. To compensate for the deficiencies of stationary sensors, highly maneuverable mobile sensors can be introduced, installed on different mobile carriers to perform cruise operations. Monitoring routes and times can be flexibly adjusted according to mission requirements, quickly entering areas that stationary sensors cannot cover.

During field deployment, mobile sensors should be firmly secured to the mobile carrier (such as with industrial-strength magnets or other fixtures) to avoid loosening or falling during transit. If carried by drones for cruising, in addition to ensuring the equipment is firmly secured, relevant registration, operation, and flight regulations should be handled in accordance with the Ministry of Transportation and Communications' "Remote Control Drone Management Regulations" to ensure legal operation and flight safety. Since wind speed and vehicle speed affect the monitoring results of mobile sensors, stationary sensors cannot be directly installed on mobile carriers for monitoring operations. Structural improvements must be made to allow airflow to enter the mobile sensor stably for monitoring, ensuring the quality of sensing data. Due to the high maneuverability of mobile sensors, they are particularly suitable for impact range assessment of sudden pollution events such as fires or chemical accidents, or for identifying potential pollution hotspots. Overall, by combining regulatory monitoring stations, stationary sensors, and mobile sensors, a complementary air quality monitoring system can be formed. Regulatory monitoring stations play a core and baseline role, stationary sensors provide stable and long-term basic monitoring, and mobile sensors reinforce spatial flexibility and real-time response capabilities. This assists local environmental protection bureaus in more precisely mastering pollution distribution, enhancing the effectiveness of pollution control, inspection, and environmental governance, and providing a more comfortable living environment for the public.

10.2 Auxiliary Air Quality Forecasting and Simulation Applications

Current air quality forecasting is primarily based on Atmospheric Chemical Transport Models (CTM). By utilizing meteorological data, emission inventories, and topographic conditions, these models simulate the generation and transport of pollutants to produce large-scale forecasting results at regional or national levels. However, CTMs still face several limitations; for instance, insufficient temporal and spatial resolution in emission inventories makes it difficult to rapidly reflect local emissions and presents challenges in capturing small-scale meteorological features. Furthermore, forecasting results exhibit uncertainty when facing sudden pollution events or drastic meteorological changes, while also relying on high-cost regulatory monitoring stations for calibration. When monitoring density is insufficient, forecasting precision is also affected.

With the large-scale deployment of sensors, high-spatiotemporal resolution data has become a basis for improving forecasting models. Sensors provide information on small-scale pollution concentration variations, such as in streets or communities, capturing local emissions and short-term changes that are easily overlooked by regulatory monitoring stations. This assists in enhancing the estimation of pollution emissions and the simulation of near-surface pollution concentrations. Additionally, through dynamic adjustments such as data assimilation techniques and AI machine learning calibration, sensing data can be effectively integrated with Atmospheric Chemical Transport Models. This integration improves spatial resolution, strengthens the response capability to local pollution events, and increases forecasting accuracy. Overall, while sensors cannot replace traditional forecasting models, they can enhance the accuracy of existing simulations and forecasts. By combining sensing data with chemical transport models, national air quality forecasting can achieve scientific rigor, precision, and real-time performance to support more comprehensive pollution control and decision-making applications. Furthermore, the long-term accumulated aerosol chemical composition observation data from regulatory monitoring stations serves as an important foundation for pollution characteristic analysis and trend assessment. By combining high spatiotemporal resolution sensing data with statistical estimation, model simulation, or machine learning methods, exposure risk assessments for different environments can be further analyzed, serving as a reference for research on public health impacts and the development of pollution improvement policies.

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