Insights from the development of an innovative air quality monitoring system

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Keywords: urban air pollution, smart city, air quality monitoring, particulate pollution, population exposure, Region of Attica -GR.

Abstract

The existing air pollution monitoring network in the Attica basin, overseen by the Ministry of the Environment (MEEN) consists of certified and high-cost sensors, and consequently is not dense enough. At the same time, it offers no easily accessible information to the citizens or representative data on population exposure. Low cost IoT sensors present a solution to the density issue, even though Quality Assurance/Quality Control (QA/QC) is required to ensure accuracy of their measurements, but face challenges related to their deployment. Within that frame, the Smart Stations were developed by the FAIRCITY (ATTP4-0360457) project aiming to bridge Smart City Services (e.g., free internet, information, wheelchair/devices charging) with continuous air quality monitoring and exposure assessment. The smart info-kiosk benches powered by sunlight (manufactured by a Greek Innovation Company) were thus employed where low cost IoT sensors were embedded, offering a unique opportunity to monitor air quality at the level where citizens live. This endeavor faced several challenges related to the design of smart stations, the network, the information to be conveyed to the public and the scientific value of the data collected.

1. Introduction

1.1 State-of-the-art

The burgeoning growth of urban areas presents a myriad of challenges, none more pressing than the need to mitigate the adverse effects of air pollution on public health and environmental sustainability. As cities strive to embrace smart solutions to enhance liveability and well-being, innovative approaches to air quality monitoring have emerged as a focal point of urban development. There are many methods for urban air pollution monitoring and assessment of personal exposure (Xie et al, 2017, Gulia et al, 2020) as well as approaches for the design of urban air quality networks (Mofarrah and Husain 2010, Duyzer et al 2015). In the past, monitoring devices were large, complex, and expensive. However, the sensors technology has changed dramatically and low-cost devices that can provide real-time information for pollutants of interest has increased data availability and access (Snyder et al, 2024). Moreover, information towards citizens is now facilitated by smart devices and thus more accessible as is the need to raise awareness and train. In this context, the convergence of advanced technology and urban infrastructure has paved the way for the development of a smart air pollution monitoring network utilizing information benches, the “Smart Stations”. Up to now few networks have been developed worldwide. At Maricopa County (USA) air quality educational kiosks have been designed to provide useful information about local air quality. A small device checks the air quality and displays data on one of the display screens in a user-friendly way. To date, there are two fixed kiosks and one mobile that is used for various educational events. More information can be found at https://www.maricopa.gov/5936/Air-Quality-Educational-Kiosks. In Boston (USA), the Environment Department, has launched a widget for measuring air quality with the aim of providing more accessible information to citizens. Digital kiosks that utilize solar energy are used as a smart communication tool displaying real-time air quality information forecasts as well as advertisements (https://www.boston.gov/news/access-air-quality-information-soofa-digital-sign-near-you).

The study of the local air quality is of great importance since air pollution has harmful effects on human health and may cause, trigger, or deteriorate diseases ranging from cardiovascular to pulmonal diseases, whereas it is a leading contributor to premature mortality (Bala et al., 2021; Orach et al., 2021; Parcal et al., 2013; WHO 2013). Furthermore, the serious effects of air pollutants (O_3) in the ecosystem, on vegetation and biodiversity have been already recorded (Agathokleous et al., 2020; Sicard et al., 2021). The effects of air pollution on daily life, in terms of quality of life, should also been considered (Bala et al., 2021). These issues become more relevant in the urban environment where many anthropogenic pollutant sources are concentrated usually in a relatively small area. This leads to social inequalities and the creation of areas of degraded air quality. Finally, among the local authorities' priorities are the provision of high-quality services. Even when infrastructures and plans exist their implementation is not always possible due to the lack of the scientific knowledge, trained staff and/or the funds. Thus, it is with no doubt, that continuous and direct monitoring of air quality with the aid of dense smart networks is a critical contribution to the estimation of the risk caused by the exposure to air pollution, to analyse possible impacts to public health.

This paper aims to shed light on the insights garnered during the preparatory phase of developing a smart air quality monitoring system, namely the Smart Stations, consisting of a smart info-kiosk bench and a set of low-cost pollution monitoring sensors. These benches will give information about air quality in the form of simplified indicators along with other information with the purpose of increasing citizens’ awareness, informing and help understanding the connection of air pollution with the spread of diseases. Key considerations, challenges and potential avenues for advancement are highlighted, while preparatory results from its pilot operation are presented.

1.2 Area of interest

The study is focused on the densely populated region of Attica, and it is the place where almost 4 million people live and work. Air pollutants and particulates are emitted from multiple anthropogenic activities (traffic, residential heating, industry,

https://doi.org/10.5194/isprs-archives-XLVIII-4-W10-2024-65-2024

and navigation). (Fameli & Assimakopoulos, 2016), which in parallel to the complex topography and certain meteorological conditions (e.g., winter temperature inversions), often lead to the accumulation of high pollutant concentrations. High concentrations of gaseous pollutants and particles, continue to be recorded and lead to the degradation of air quality in many areas (Pateraki et al., 2019). Environmental policies implemented so far have contributed to the gradual reduction of pollutant emissions and should be continued, enriched, and possibly tightened with the goal of environmental, aesthetic, and economic upgrading of the areas. To the best of the authors knowledge, two main air quality networks exist in the region of Attica, the National Air Quality Monitoring Network operated by the MEEN (YPEN, 2024) and the PANACEA Research Infrastructure (PANACEA, 2024). However, they are either not dense enough to provide sufficient knowledge and representative measurements for the region or only a selected pollutant is monitored. So, the hot spot areas are not depicted sufficiently and the parameters that define the air and particulate pollution episodes as well as the citizens' exposure, are not presented adequately. Citizens of Attica basin municipalities have little or no access to information on local air quality, personal exposure, and actions they could take to help improve air quality at their neighbourhood and consequently reduce the health effects.

2. Methodology

The methodology to design our Smart City Network with the aid of the Smart stations was based on the following steps: (a) Define its purpose and select the pollutants, determine the network size and the station locations. (b) Choose the monitoring equipment, establish a quality control and data management platform, as well as the parameters to be studied (e.g., exposure, risks, sources etc.). (c) Implement and monitor the network operation, review and improve and last but not least exploit and promote it.

2.1 Monitoring municipalities

The purpose of this pilot network is to monitor air quality on the level that people live, within the urban canopy and at a distance of main sources (e.g. highways) in order to capture background values. The municipalities selected present different features which include a mixture of industrial, dense residential and highly trafficked locations (Nikaia - Rentis), a mostly residential – commercial use (Korydallos) and a mostly residential with green spaces and highly trafficked streets municipality of Amarousion (Figure 1).

2.2 The Smart Stations

In this phase (b), five smart stations are being produced, combining air pollution monitoring with sharing of important information on community events, wheelchair charging, free internet, a resting shadowed bench, independently operating with a photovoltaic panel. They low-cost sensors embedded in the bench at a height of about 2.5m, measure continuously:

- ✓ Five air pollutants (CO, CO_2, NO_2, SO_2, O_3)
- ✓ Particles of three different sizes (PM_{10}, $PM_{2.5}$, PM_1) and
- ✓ Meteorological parameters (temperature, relative humidity, pressure).

Most gas sensors are electrochemical (CO, NO_2, O_3, SO_2), while CO_2 sensor is a solid-state photoacoustic sensor (the working principle is based on elastic movement of parts of it). Optical particle counting is occupied for $PM_{1.0}$, $PM_{2.5}$, PM_{10} determination. It should be noted that, as the gas sensor for O_3 also measures NO_2, a separate sensor for NO_2 measurement was occupied for more reliable results. Temperature (for all sensors) and humidity (for CO_2 sensor) are algorithm-based determined. As most of the sensors used in the FAIRCITY project are electrochemical, it is important to analyse how they operate. In general, a sensor is a device which receives a stimulus (i.e. mechanical, thermal, chemical, biological, etc.) and converts it into an electric signal (i.e. potential, electric current, conductivity, etc.). Electrochemical sensors are a subcategory of chemical sensors. Electrochemical sensors are categorized into a) potentiometric (measuring potential), b) amperometry (measuring current), c) conductometric (measuring conductivity). In all the above cases special electrodes are used on which a chemical reaction occurs (e.g. oxidation (electron loss) and/or reduction (electron gain)) or load transfer is affected by the reaction and for them to measure electric current is necessary to flow through the circuit. The optical particle counter is a device consisting of a) optical, b) electronic, c) sample management parts. It is extendedly used in a) contamination analysis, b) atmospheric analysis of liquid or gaseous particles, even when not all particles fall within the size

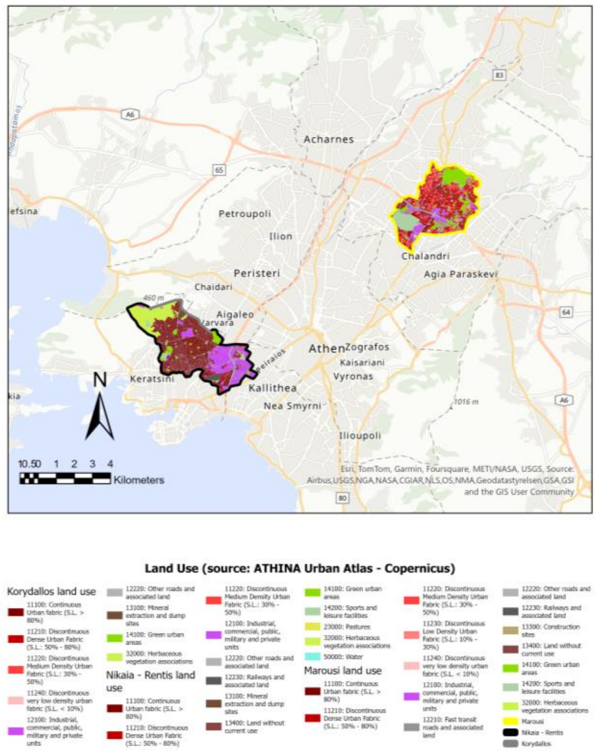


Figure 1. Land use types at the three municipalities (marousi, Nikaia – Rentis and Korydallos).

enter range. Particles separately enter the sensing zone which is illuminated by laser or incandescent (lamp) light and produce signals because of their interaction with light, which are measured and, furthermore, determine their sizes (Scarlett B., 2002). Signal depends upon a) particle dimensions and optical properties and b) operating principle (light scattering/light extinction). Number and sizes of particles are calculated with the use of calibration or fitting. Regarding the photoacoustic solid state SO_2 sensor, it operates based on the elastic movement of some of its parts. Acoustic solid-state sensors, in general, are used for a) noise detection, b) distance measurement, c) mechanical strain, d) force, e) temperature, etc.

A stimulating device (usually piezoelectric (where mechanical strain causes load or applied electric field causes mechanical distortion of piezoelectric material) urges the atoms of the solid material to oscillate and the characteristic sizes (phase, velocity, absorption coefficient) of the oscillation are affected by the stimulus. Acoustic waves have lower velocities than electromagnetic waves and this fact allows the creation of miniaturized sensors with working frequency up to 5 GHz. The Smart stations will be deployed in three different municipalities across the Attica Basin. The selected municipalities are characterised by different land use types/anthropogenic emissions sources, population densities and socio-economic conditions. As a result, the pollutants concentration patterns differ and consequently lead to differential exposure problems.
Prior to installing the stations, the sensors have operated for a period of one month next to certified air pollution instrumentation to define if required, the correction algorithm following the methodology of (Stavroulas et al., 2020).

2.3 Data collection and platform development

A crucial aspect of our approach involves the development of a robust data collection and processing platform. This platform serves as the backbone for aggregating all sensor data and facilitating real-time dissemination of air quality information to the public. The data collection platform is the central hub where all measurements obtained from the sensors installed in the smart benches are uploaded and stored. Specifically, using Python programming, a cloud-based infrastructure has been established to cater to the project's needs. The development process entails the execution of the following functions on an hourly basis:

A. *Data Transfer*. Raw data captured by the sensors in the smart stations are transferred to the cloud for storage and processing. This step ensures the seamless flow of data from the edge devices to the central repository.
B. *Data Processing*. Upon ingestion, the collected data undergoes processing to derive meaningful insights. A QA/QC protocol is followed in order to ensure the One critical operation involves the calculation of the Air Quality Index (AQI) based on pollutant concentrations recorded by the sensors.

The function used for calculating the AQI for each pollutant is as follows (Mo et al, 2020):

$$Ip = (IHI - ILO) \times \frac{CP - BLO}{BHI - BLO} + ILO \quad (1)$$

where BHI = Breakpoint concentration, greater than or equal to the given concentration.
BLO = Breakpoint concentration, smaller than or equal to the given concentration.
IHI = AQI value corresponding to BHI.
ILO = AQI value corresponding to BLO.
CP = Pollutant concentration.

The computed AQI, along with corresponding pollutant levels, is then dispatched to the respective smart stations. These stations, equipped with suitable graphical displays, promptly update the public on the prevailing air quality conditions in their vicinity.
To facilitate the functionalities outlined above, a Python program has been developed. This program orchestrates the data management processes and ensures the smooth functioning of the air quality monitoring network. Key components of the Python program include:

A. *Data Retrieval and QA/QC*. Utilizing APIs, the program retrieves sensor data from all the smart stations, which are then scanned for removal of outliers, checking of sensors' performance and identification of invalid measurements.
B. *AQI Calculation.* Leveraging predefined breakpoints for various pollutants, the program computes the AQI values, providing a comprehensive assessment of air quality. In figure 1 the AQI, calculated by the five main pollutants which are included in the European legislation (ozone, NO_2, SO_2, $PM_{2.5}$, PM_{10}) for the whole period of measurement (25/03 – 22/04/2024), is shown.
C. *Quality Assessment.* Based on the highest AQI recorded, the program determines the overall air quality level using predefined quality thresholds.
D. *Output Generation.* Finally, the program generates output in JSON format, containing pertinent information such as timestamp, AQI, pollutant concentrations, and air quality status. These outputs are then disseminated to the smart stations for public consumption.

2.4 Risk assessment

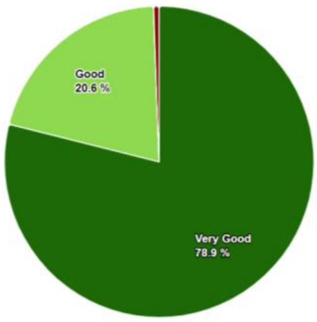
Data from the smart stations are used to assess the risk on public health based on the methodology of the exposure – response functions (Ru et al., 2023). To that end, the software AirQ+ (WHO 2020), is applied. In this work the calculations were for the Regional Unit of Pireaus (municipalities of Korydallos and Nikaia – Rentis are included). AirQ+ is used to: 1) design the most suitable exposure scenarios for the studied population, 2) analyse the parameters of assessment that are engaged in the risk calculation, and 3) quantify the health impacts that may occur due to the exposure to the studied pollutants that have been identified and measured by the smart benches. In particularly, the data used for the designed scenario are the following: $PM_{2.5}$ and NO_2 measured concentrations provided by the Hellenic Ministry of the Environment and Energy (https://ypen.gov.gr/perivallon/poiotita-tis-atmosfairas/dedomena-metriseon-atmosfairikis-rypansis/) as well as population informative data derived by the Greek Statistical Authority for the selected regional unit (www.statistics.gr, exposure duration, population density, hospital admissions for the year 2022, and area size in km^2).

3. Discussion of first results

The scope of the present study is to show the AQI in a simplified way. According to early sensors readings, the daily AQI in the Municipality of Korydallos and at the testing site at the centre of Athens (National Observatory of Athens station at Thissio) was very good during the period from 25/03/2024 till 22/04/2024 (Figure 1). It is obvious that no severe pollution episodes were recorded. It should be mentioned that the index ranges from 1 (good) to 6 (extremely poor).

Of course, a deeper look at the hourly readings reveals significant discrepancies. This is an anticipated occurrence since air quality is influenced not just by human activities but also by local meteorological conditions, which alter the overall picture of air quality in each place. For example, South African dust has a significant influence on PM levels, which occurred during the early operation stages of the sensors and the pilot smart station.

In figures 3 to 6 the mean daily concentrations for selected air pollutants and particles used in the AQI calculations is presented. Dark green columns refer to values below the target limit value while the light green columns represent values above the target value, which is 15 μg/m^3 for $PM_{2.5}$ (24hr average), and 40 μg/m^3 NO_2 (annual), respectively.



POLLUTANT	INDEX LEVEL (based on pollutant concentrations in µg/m3)					
	1 Very good	2 Good	3 Medium	4 Poor	5 Very Poor	6 Extremely Poor
Ozone (O_3)	0-50	50-100	100-130	130-240	240-380	380-800
Nitrogen dioxide (NO_2)	0-40	40-90	90-120	120-230	230-340	340-1000
Sulphur dioxide (SO_2)	0-100	100-200	200-350	350-500	500-750	750-1250
Particules less than 10 µm (PM_{10})	0-20	20-40	40-50	50-100	100-150	150-1200
Particules less than 2.5 µm ($PM_{2.5}$)	0-10	10-20	20-25	25-50	50-75	75-800

Figure 2. The AQI as calculated by the air pollutants and particles measured by the set of sensors and the supsequent classes based on the measured concentrations for each pollutant.

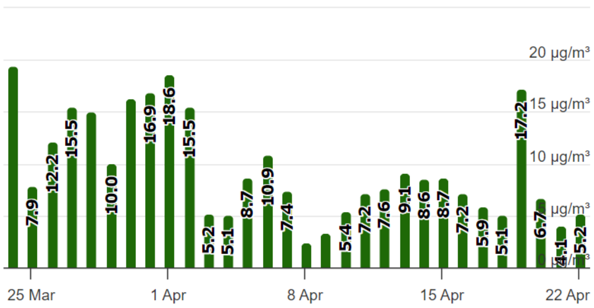


Figure 3. Mean daily PM_{10} concentrations from the five air quality sets of sensors and for the period 25/03 – 22/04/2024.

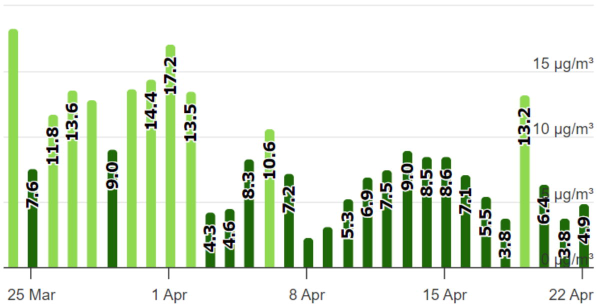


Figure 4. Mean daily $PM_{2.5}$ concentrations from the five air quality sets of sensors and for the period 25/03 – 22/04/2024.

According to figures 3 and 4, the mean daily PM_{10} concentrations never exceeded the WHO daily regulation limit. Even though there was a major event in South Africa dust, the overall variation is excellent. The sensors are in the city centre, yet there is less traffic and adequate germination in the area.

The burning of fossil fuels (coal, gas, and oil), particularly diesel used in automobiles, is the primary source of nitrogen oxide emissions caused by human activities. Concerning SO_2 concentrations, higher values were measured at the end of March while for the rest period values remained quite low (Figure 5). Due to the traffic in the surrounding area the NO_2 concentration values exceeded the EU limit of 40 μg/m^3, which must be noted is on an annual basis (Figure 6).

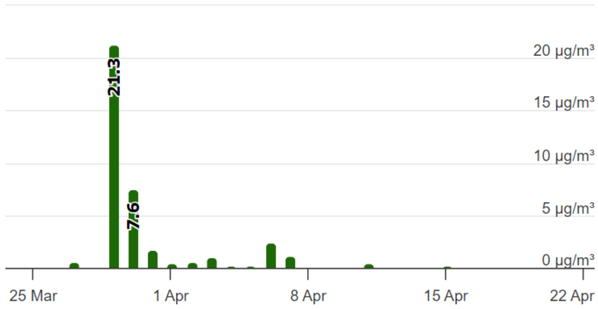


Figure 5. Mean daily SO_2 concentrations from the five air quality sets of sensors and for the period 25/03 – 22/04/2024.

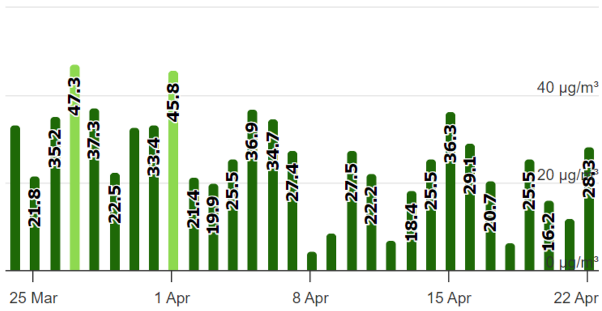


Figure 6. Mean daily NO_2 concentrations from the five air quality sets of sensors and for the period 25/03 – 22/04/2024.

Concerning the risk assessment, preliminary results are presented in figures 7 and 8 and the exposure to $PM_{2.5}$, is investigated. It should be clarified that the short-term effects of $PM_{2.5}$ and NO_2 pollutants on human health are estimated as health consequences of excess and depend on the pollutant. Health consequences involve Hospital Admissions due to respiratory diseases caused by the exposure to $PM_{2.5}$ (Figure 7), Work Days Lost due to exposure to $PM_{2.5}$ (Figure 8). Preliminary results revealed that the correlation of pollutants' concentration to the health impacts is quite significant, indicating the direct impact of the studied pollutants to the chosen health endpoints.

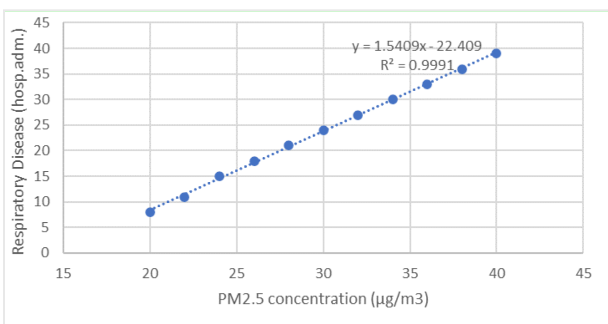


Figure 7. Health impacts attributable to the exposure to air pollutants ($PM_{2.5}$ – respiratory diseases).

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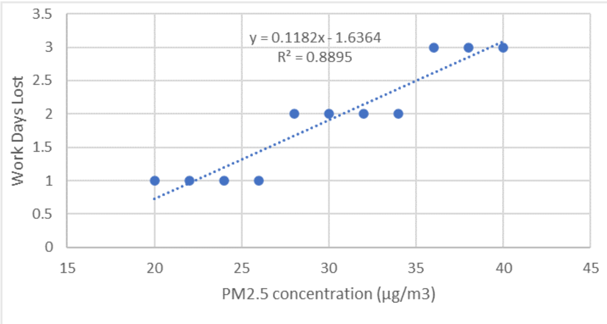

Figure 8. Health impacts attributable to the exposure to air pollutants ($PM_{2.5}$ – Work Days Lost).

4. Concluding Remarks

The first small smart network of info-kiosks and air quality sensors in the Attica basin has been established. It aims at producing more data, easily reachable on exposure and impact of anthropogenic activities. For such a network to serve its purpose, the location of measurements is important and should have two main characteristics: be accessible to the public and take measurements at the level of human activities. Collaboration with municipalities is of the outmost importance to promote awareness and exchange of knowledge and support. Low-cost sensors are a good solution since technology allows for reliable measurements, but regular inspection and quality control is required. Management of the big volume of existing (official) and new (smart stations) data in a common platform that allows for various analyses (exposure, exceedances, etc) ensures the longevity of the endeavour, the application of A.I. tools for statistical analyses and the combination of different layers of data for more complex studies. Thus, continuous monitoring of air quality is a crucial component for the design of mitigation techniques.

Acknowledgements

The present study "*FAIRCITY Future smart city environment: Innovative air pollution monitoring network using info kiosk benches (ATTP4-0360457)*" has been financed by the Regional Operational Programme Attica 2014-2020 (PEP Attikis) – NSRF 2014-2020

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