Augmented Reality for Air Quality Monitoring: Case Study in the Marche Region (Italy)

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Abstract

Augmented Reality (AR) allows the real world to be enhanced through the overlapping of digital information generated by an algorithm or software amplifying the user's perception. In this research, the potential of AR is exploited by applying it to the problem of air pollution visualization to raise awareness of the issue. It is well known that the principal sources of air pollution include industry, domestic heating, traffic, production processes and more others. According to European Environment Agency, air pollution is the largest environmental health risk in Europe in 2022[1] affecting respiratory and cardiovascular diseases and premature deaths. A suitable combination of GIS-based procedures for data analysis and georeferencing, AR systems for the visualization and exploitation of the results, can be a strategic driver. The research presented in this paper has been experimented in the Marche Region, in the central part of Italy, and in particular the city of Ancona. The pollutant data collected come from 17 Agenzia Regionale per la Protezione Ambientale delle Marche (ARPAM) meteorological ground-based stations located in Marche Region. The data processing have been executed using the software ArcGis Pro instead of a 3D City Model has been acquired from the online 3D ArcGIS platform. According to the Dlgs.155/2010 regulation, the AQI index (Air Quality Index) has been provided by the interpolation of the meteorological ground stations data. The visualization phase has been tackled exploiting in a WebGIS platform and an APP by AR. A 3D immersive visualization is made using five AQI level of air quality (excellent, good, fair, poor, bad) in order to increase the urban sensing.

1. Introduction

Spatial mapping in space and time of air quality information is becoming more and more important. Among different visualization methods, novel geo–visualization tools that exploit XR (eXtended Reality) solutions can play a pivotal role to increase the comprehension of this phenomena and, at the same time, can increase awareness of different actors, both stakeholders and citizens. In this way, the air quality information could be shared with experts from other disciplines to foster improvements in other scientific fields, but not only, also with users, to feel better the life. Social impact can improve public users and decision makers awareness by augmented perception of the environmental factors within spatial and temporal limits. For example, the use of XR can safely expose users to various virtual situations of risks and improve the decision-making capacity. One of recent examples is the project that regards the New York Times interactive website and the "Aire" APP (Torres et al., 2019).

In this context, we present our research that is conducted within the Italian Project of National Interest (PRIN) "GeoAIr" include many tasks and some working groups to provide the research community with rigorous data resources regarding air quality and, with strategic objective, to offer free access to these data to a wider public, using innovative technologies. In particular, the paper is focused on the research of one of these working groups, to build an extended reality environment transferring knowledge to different users.

XR technology gives an innovative way to make virtual and safe immersive environment where to live different air pollution scenarios. The testing scenario is designed to provide a concrete example of the potential of the Geomatics to raising awareness through virtual experiences, where space and time play important role. The aim is to increase risk perception (situation awareness) and decision-making capacity during a daily situation, not perceivable with the naked eye. Technology used to create a digital training system is based initially on a GIS database, interoperable and constantly updated. It is then transferred on a WebGIS platform and an APP. To geolocate the current pollutant situation and to provide a visualization experience, a useful APP is given, for both the public and decision makers. The proposed application aims to harness the power of Augmented Reality (AR) to provide users with an intuitive and immersive way to visualize air quality data. Using Unity's AR Foundation, the APP allows users to see real-time air quality information directly overlaid on their surroundings through their smartphone camera. This innovative approach helps users better understand the composition of the air they breathe, highlighting pollutants such as NO2, PM10, and PM2.5. This paper describes the data management pipeline together with a first location-based service to validate the methodology and define the standard procedure to bring GIS based data into AR environment.

The quality of experience will be verified by evaluating the experience feedback and response of users, by testing the technology accessibility, the level of user-friendliness, the perception of the environment and the readability.

2. State of the art

The goal of this research wants to show the potential and, at the same time, to learn about strategy and trends related the use of XR for environmental topics. We have analyzed which types of

[1] https://www.eea.europa.eu/publications/air-quality-in-europe-2022/health-impacts-of-air-pollution

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platforms and devices exist and which ones meet our requirements and our needs and then what tools should be used in the process. We talk about trends in XR from the point of view of people or users, activities and technology. It is important to understand the fundamentals, the terminology about AR, VR, MR, XR, and the Reality-Virtuality Continuum. Selecting appropriate platforms, devices, and development tools used in XR across various fields, expressing the potential issues and user perspective, activity focus, and technology integration surrounding XR technologies.

Overall, it is important to understand the XR technologies, to explore their applications and potential, and provide the knowledge to approach XR projects strategically, considering design, development, and potential challenges. What is XR? A recurring question. Probably Virtual Reality (VR) and Augmented Reality (AR) are most familiar. We often say AR/VR, but there are actually very different technologies associated with these terms. So, when we talk about VR, we always think of the idea of replacing reality around the user. VR creates a fully computer-generated virtual world, replacing the user's perception of the real world. It emphasizes user autonomy and agency through features like head tracking, body input (controllers, hand gestures, voice), and provides a sense of presence through visual, audio, and haptic feedback. AR enhances the real world by overlaying virtual content on top of it. The user sees a composite view of both the real and virtual worlds. It allows for real-time interaction with the virtual elements and uses 3D registration to align virtual objects with the physical world. Mixed Reality (MR) is a term with various interpretations. In general, it refers to a spectrum between AR and VR. On one end, there's minimal augmentation of the real world (closer to AR). On the other end, there's a mostly virtual environment with some real-world elements incorporated (closer to VR). Milgram's definition of MR encompasses AR and Augmented Virtuality (AV), but not VR (Milgram et al., 1995).

The AV is the inverse of AR; it is mainly virtual and we augment the virtual with physical content. It could be a form of AV, when you actually transfer the coordinates of the real world and this can really be very good at getting into virtual reality, so much so that one day we may not be able to distinguish between the virtual world and the real world. Now, in this transition from AR to AV, we can find tablets and smartphones that produce augmented reality content.

Now Extended Reality (XR) is a term where "X" can represent AR, VR, or MR depending on the context. XR () is an umbrella term encompassing technologies that alter reality by adding computer-generated elements.

XR refers to everything that is augmenting the real world, including full virtual reality and X is really just a wild card for AR, VR or MR. There are many different XR technologies and applications. One notion helpful for building a better understanding of the XR space is that of the Reality–Virtuality Continuum that was first described by Paul Milgram in 1994 in the research literature (Milgram et al., 1995) (Figure 1). By classifying XR Apps based on the continuum, you can gain insights into their design, technical requirements and potential applications. For instance, AR Apps typically require strong environmental understanding to accurately overlay virtual content onto the real world. VR Apps, on the other hand, focus

Figure 1. The Reality-Virtuality Continuum spectrum.

on creating immersive virtual experiences that may not require as much real-world interaction.

XR is an industry with hundreds of companies, tens of thousands of employees, with some billion in investments. A key challenge for Europe, is its highly fragmented participation: in its policies, technology development, and funding. There is also a lack of interoperability for wide-scale technology adoption and standards.

There is a proliferation of new devices with minimal differences in screen resolution and field of view, which are some of the key factors. For example, it is technically very difficult to improve and increase the field of view, but many technical aspects are improving rapidly. Hand, finger, and eye tracking is becoming a standard, and it's actually quite good already, but we still need to make much more progress. The challenges in the industry and in the classification system for XR technologies underline some key points: there's a lot of hype and misleading information surrounding XR technologies. New devices often have minimal improvements while technical limitations remain, like limited environmental understanding. The classification systems are summarized in four categories:

- devices: standalone devices (e.g., Oculus) vs. integrated ones (e.g., AR Apps on phones);
- platforms: systems where XR applications run on (e.g., Windows Mixed Reality, WebXR);
- applications (XR Apps): software specifically designed for XR experiences;
- tools: development tools used to create XR applications.

This classification helps understand the XR landscape. We can interact with AR able devices and Apps through the smartphones (Web browsers or dedicated AR Apps). The activity encourages trying an AR App on a smartphone to gain firsthand experience. There are two main ways to experience AR on smartphone: the first one is via Web browser and does not require any installation, the second one is installing an AR App or an App with AR mode.

Another paper collects and analyzes different working definitions of MR adopted in industry and research based on a review of existing literature on the topic and conversations with experts (Speicher, 2019). Some treat MR as a synonym to AR leaving out a significant portion of the Reality–Virtuality Continuum that is often identified as AV. Some include VR when they speak of MR. There is still a confusion around and establish a better understanding of the term MR. Overall, this emphasizes the lack of a single, agreed-upon definition for MR. Traditionally, discussions about AR, VR, and MR have focused on graphics and visuals. However, experts acknowledge the importance of incorporating other senses in MR experiences. The paper concludes that there's no single, universally accepted definition of MR. The goal is to provide researchers and practitioners with tools to think about, discuss, and compare MR experiences more effectively, even though the exact definition of MR itself might be debated. This approach is like

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how the "Time/Space Matrix" helped categorize different types of groupware collaboration.
Since pollution is one of the biggest problems, humanity faces, it is important to find strategies to raise audience awareness that are as effective and immediate as possible (Sicard et al., 2022). It is known in clinical literature that exposure to fine dust due to air pollution causes premature deaths due to the development of cardiovascular diseases (Franklinet al., 2015; Cakaj et al., 2023; Alahmad et al., 2023). One of the possible strategies to sensitise the citizens is the combination of data visualisation of the pollutant concentration with an AR platform. This is because an AR application is able to enhance the real world by overlaying virtual content on top of it. The true first difficulty that you may encounter when an air pollution analysis starts, it is the collection of data. There are not enough meteorological or pollution ground monitoring stations on the territory and in case in which they exist are poorly distributed (Zeng, 2017). An experience like this application is described in (Mathews, 2021). They proposed an AR application, able of completely immersing them in an interactive and engaging scenario. Since everyone owns an Android device, the idea to use an APP to view the data seems to be a good choice. A similar approach based in this case on a virtual reality system is the one conducted by (Pochwatko et al., 2022) through a transdisciplinary scientific project. Aware of the fact that, despite the insistent propaganda against environmental pollution, people do not seem to become sensitised, they exploit VR in combination with a high level of physiological and behavioural control. Another kind of approach is provided by other researchers that decided to develop a serious AR game for children. They succeeded to greatly stimulate them making the intangible visible to child's eyes in parallel with a knowledge of the air pollution problem (Fernandes et al., 2023).

3. Case study

This research is set in a region of central Italy, specifically in Marche Region on the east coast of the peninsula. Data values of the main pollutants in the Marche Region, collected by ARPA in 2022, show that 100% of the ground stations don’t exceed the permissible concentration limits.[2] That area has been selected just as an example of where to apply the AR developed APP, tried in the city of Ancona. The methodology applied is represented in the Figure 2 starting from the first phase that has been the data collection, passing through the data processing, GIS implementation and the virtual representation.

3.1 Data collection

The data have been collected from meteorological ground-based stations. In order, to make a better interpolation of the data, other stations, belonging to regions bordering the Marche Region, have been considered too. As has been mentioned in section 2, the first difficulty encountered has been the data collection. Stations are few and badly distributed, so it is not easy to interpolate the data as truthfully as possible. Marche Region has 17 meteorological ground stations, of which 6 on rural land, 4 on urban land, 2 on industrial land and 5 in the urban traffic area (Figure 3). They have been resulted to not be enough to cover the area in detail. This is the reason why it has been decided to take in consideration of some other meteorological ground stations located in the closed other Regions. The parameters collected are monthly average concentration values of PM 10, PM 2.5 and NO2, referred to June 2023. The data analysis and visualization have been limited only to these three pollutants (PM 10, PM 2.5 and NO2) because the others were not available for considered period. The pollutants taken into consideration in this research have different sources.

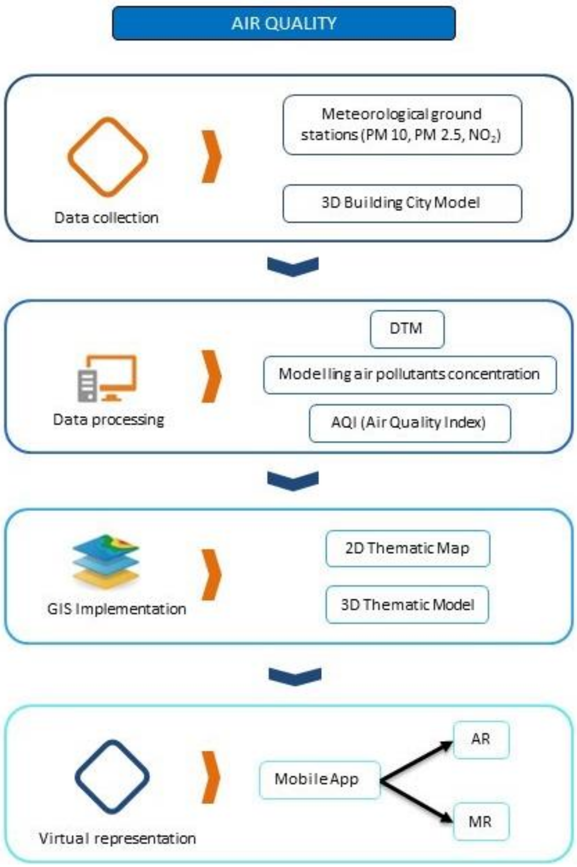

Figure 2. Methodology outline.

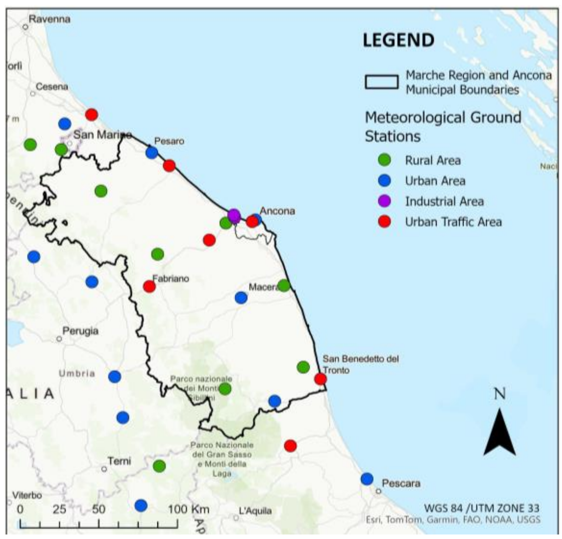

Figure 3. Spatial representation of meteorological ground stations.

The particulate matter gets its name PM10 or PM2.5 based on the diameter of its particles whose unit of measurement is the micron. PM10 comes from vehicles, industrial processes and natural phenomena. PM 2.5 has the same sources as PM10 but

[2]https://www.snpambiente.it/uncategorized/qualita-dellaria-nelle-marche-nel-2022-i-primi-dati/

also derives from combustion. NO2 comes from high temperature combustion and is a toxic gas. As mentioned previously, the main problem encountered is the lack of data or insufficient data. To mediate this problem, it was necessary to carry out a spatial analysis process. The concentration values of each pollutant, detected by the meteorological ground stations, have been interpolated through a geoprocessing activity on GIS platform by IDW method (Inverse Distance Weighted). This process allows us to exploit the knowledge of the values of known points to determine through statistics the value in other points for which we do not have information. In this way it was possible to have information relating to the concentration of each pollutant on a continuous map and not only on the points where the meteorological stations are present.

In addition to the pollutants concentration data there is the 3D Building City Model. The three-dimensional urban modelling helps to expand the data collection to develop an immersive 3D Model useful for the representation of air pollution by AR.. Once the data collection phase has been concluded, the next phase has been the processing phase.

3.2 Data processing (pollution)

The digital terrain model (DTM) has been used to give a representation of the elevations of the land. The interpolation of the punctual data of the meteorological ground stations has given a continuous thematic map over the whole area. So, the data, relating to the concentration of pollutants, have been represented in 2D and, obviously, in 3D thematic map in GIS. Due to the interpolation the whole area is composed of polygonal features. Each of these polygons has a pollutant concentration value. An example of how a representation of an air pollutant concentration above an area is described in section 4.1. The polygon pollutant concentration value has been then inserted into the equation (1) for calculating the Air Quality Index (AQI) according to the Dlgs.155/2010 regulation[3]. For each one of the pollutants the regulation provides a legal value limit concentration. The limits value for the pollutants took in consideration in this paper (PM10, PM2.5 and NO2) are the following:

- PM2.5: 25 µg/m³
- PM10: 50 µg/m³
- NO2: 200 µg/m³

$$\text{AQI} = \frac{measured\ concentration}{legal\ limits} \times 100 \quad , \quad (1)$$

where *AQI* = Air Quality Index

The equation is based on a percentage of the ratio between the measured concentrations over the legal limits. The measured concentration is the concentration in µg/m³ collected by the meteorological ground stations for each hour. The legal limits are those concentration levels of pollutants that should not be exceeded. For example, for PM10 the limit of 50 µg/m³ should not be surpassed more than 35 times a year according to the Dlgs.155/2010 regulation.

Once the AQI value has been calculated, the value obtained by equation (1) must to be compare to the value of the reference range scale in order to interpret how is the quality air. Following the reference scale range classes:

- Excellent: AQI< 30
- Good: 34 ≤ AQI < 66
- Fair: 67 ≤ AQI < 99
- Poor: 99 ≤ AQI < 150
- Bad: AQI > 150

The quality of the air in an area of interest is the worst AQI value referred to any single pollutant considered. In our case, having considered only three air pollutants (PM10, PM2.5 and NO2), the result of the air quality is the worst value between AQI_{PM10}, $AQI_{PM2.5}$ and AQI_{NO2}. The formula is (2).

$$\text{AQI} = [\text{MAX}(AQI_{PM10}; AQI_{NO2}; AQI_{PM2.5})] \quad , \quad (2)$$

4. Thematic representation

In a GIS environment, pollutant concentration data have been interpolated by means of the geostatistical analysis method IDW (Inverse Distance Weighted), using ArcGIS Pro software. A 3D map has been built using DTM, topographic basemap and the 3D Building City Model from the ArcGIS Online Atlas.

4.1 GIS 2D

An example of a pollutant concentration representation resulting from IDW interpolation is shown in Figure 4. The figure refers to the monthly daily average value of PM10.

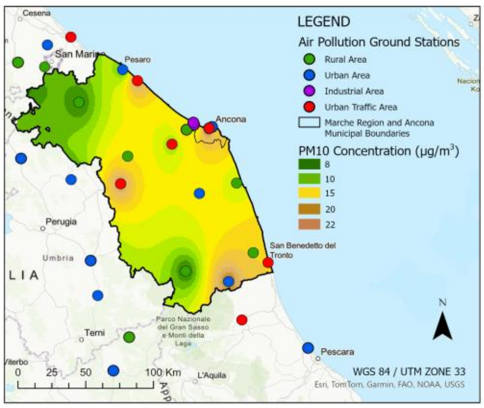

Figure 4. PM10 concentration on Marche Region.

4.2 GIS 3D

Dealing with the 3D GIS environment, three types of data visualisation have been realised. The first one is in Figure 5 and it represents the 3D model of the PM10 concentration. It is notable that the base map area is visible in different parts with different base colours. It depends on the PM10 concentration values which is different from a part to another. It is not an immediate visualisation of the data because the 3D GIS environment is not able to put a legend on it. For this reason, the use of a WebApp gives to the user the possibility to be immersed but also to interact with the data. Figure 6 gives another type of visualization showing the 3D model of the pollutants analysed (PM10, PM2.5 and NO2). Each coloured sphere represents a pollutant. The yellow sphere is the PM10, the green sphere is the NO2 and the orange sphere is the PM2.5. The value concentration increases linearly in size as the concentration value increases. In this type of visualization, a quickly comprehension of the pollutant condition is possible. It is visible the difference in value of each pollutant comparing the size of the spheres and seeing how they can change along the

[3]https://www.gazzettaufficiale.it/eli/id/2010/09/15/010G0177/sg

street. The last visualization refers to the whole AQI representation. This value is the worst AQI defined by equation (2) in section 3.2. The AQI is represented by the spheres and in base on their value the air quality can be "Excellent", "Good", "Fair", "Poor" or "Bad". In the case represented in Figure 7 the AQI goes from areas in which is "Excellent" to areas in which is "Good".

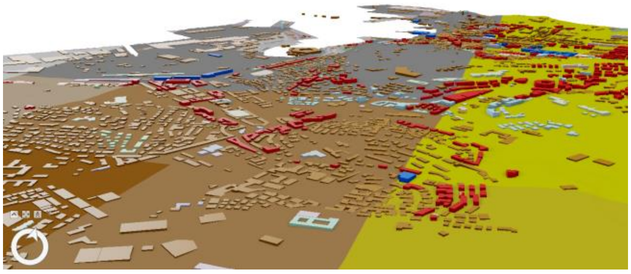

Figure 5. 3D thematic representation of PM10 concentration on Marche Region.

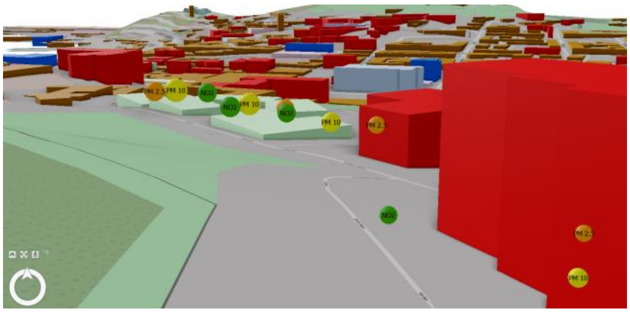

Figure 6. 3D thematic representation of PM10, PM2.5 and NO2 concentration on Marche Region.

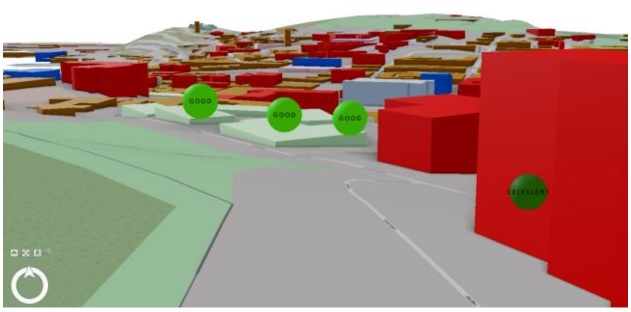

Figure 7. 3D thematic representation of the worst AQI calculated by equation (2) on Marche Region.

5. Virtual representation

The further implementation to exploit GIS data is the AR visualization, aimed at increasing user awareness in urban environments for aspects such as air pollution. The research wants to create a prototype Web application to explore if users are able to understand the real condition about an aspect of urban environment by using AR.

The Web application has to be accessible from anywhere when an internet connection is available and the users has to be able to experience immersive AR with their mobile device. The opportunity for AR usage lies in environmental communications. Mobile AR can supplement efforts of creating environment awareness through mobile applications. This can increase the opportunity for the message to reach a wide range of people. The objectives can be to investigate the possibility of using AR with WebXR and compatible devices to improve the user's awareness about aspects, such as air quality in the urban area.

Various augmented reality companies focus on providing applications that are easy to use and enhance the users' perception of their surroundings. There are different types of AR relevant to our project. It is important to establish the need, using AR, to raise awareness about urban environmental issues, to develop a Web application with immersive AR.

The WebXR definition is in relation to WebVR, and its role in XR highlighting advantages: supporting both AR and VR and eliminating the need for additional plugins. Some limitations are that WebXR is still in its early stages. WebXR is compatible with AR devices and it makes it a suitable choice for developing our prototype that visualizes air quality data in the real world **(**Maclntyre, 2018**).**

The key features of the APP proposed in this paper and called GeoAIr, are the following:

- Location-Based Air Quality Detection
- Augmented Reality Visualization
- Interactive Pollutant Information
- Real-Time Data Integration

Upon launching the APP GeoAIr, it automatically fetches the user's current location using the device's GPS functionality. This enables the application to provide location-specific air quality data. The APP GeoAIr requires the necessary permissions to access the user's location and camera to ensure a seamless user experience.

Using AR Foundation in Unity, the application visualizes air pollutants as coloured bubbles floating in the user's environment. The test has been made in the city of Ancona (Marche Region – Italy) (Figure 8). Each type of pollutant is represented by a distinct colour: red for NO2, yellow for PM10, and green for PM2.5. This colour-coding system allows users to identify different pollutants quickly and easily in their proximity.

When a user clicks on a bubble, the APP GeoAIr displays detailed information about the pollutant, including its name, current concentration, potential health impacts, and whether it is considered safe or harmful. This interactive feature will educate users on the different types of air pollutants and their effects on health, empowering them to make informed decisions about their environment.

The APP GeoAIr integrates with a reliable air quality API, such as AirVisual or OpenWeatherMap, to fetch real-time data. This ensures that the information presented to users is current and accurate. The data will be processed to determine the concentration levels of NO2, PM10, and PM2.5 in the user's location.

For what concerns the design and the user experience, the considerations made have been as follows. The design of the APP GeoAIr focuses on creating a visually appealing and user-friendly interface. The bubbles representing pollutants are designed to be easily distinguishable by colour and size, indicating their concentration levels. The APP GeoAIr ensures smooth and intuitive interactions with the AR elements. When a user clicks on a bubble, a pop-up appears with detailed information about the pollutant. This interaction is accompanied by a brief animation to enhance user engagement. Immediate feedback is provided when users interact with the bubbles. This includes displaying a pop-up with pollutant information and potential health impacts. The feedback mechanism is designed to be responsive and informative, ensuring that users receive relevant information promptly.

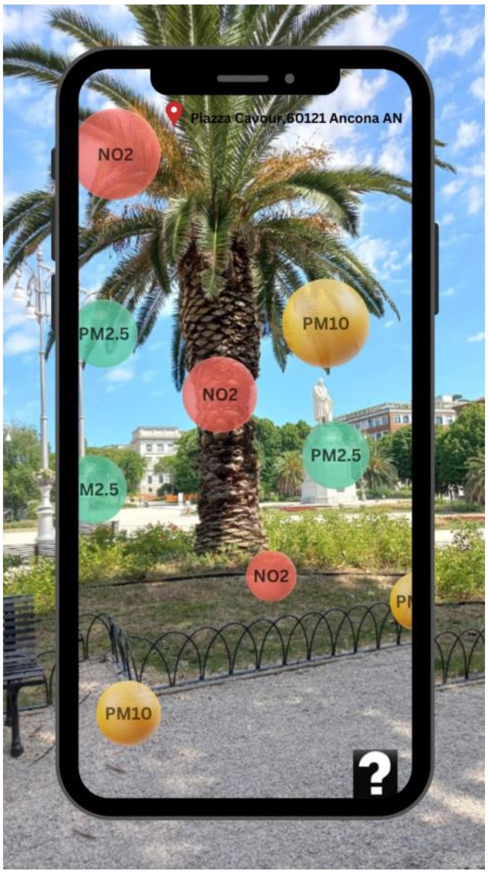

Figure 8. APP GeoAIR visualizes the pollutants by AR in Ancona (Marche Region – Italy).

5.1 Technical components

- AR Foundation is used to create the AR experience. This toolkit within Unity allows for the development of cross-platform AR applications, providing the necessary tools to detect and track the user's environment and overlay digital content onto it.
- To obtain real-time air quality data, the APP GeoAIr is connected to an air quality API. The chosen API provides comprehensive data on NO2, PM10, and PM2.5 levels. This data is parsed and used to generate the visualizations within the APP.
- The APP GeoAIr utilizes the device's GPS to determine the user's current location and the camera to enable the AR visualization. These functionalities are crucial for providing a personalized and immersive user experience.
- The real-time data fetched from the API is processed to display the appropriate concentration levels of NO2, PM10, and PM2.5. The APP GeoAIr interprets this data to create the coloured bubbles representing different pollutants.

The development plan of the APP GeoAIr has been based on five steps. The first step (Research and Planning) is the initial phase which involves finalizing the APP concept and features, selecting a suitable air quality API, and planning the AR experience. This phase sets the foundation for the subsequent development steps. The second step is the Prototype Development. Here a basic prototype is developed to test the AR functionality and data fetching capabilities. Location detection and camera access are implemented to ensure the APP GeoAir can provide personalized experiences. The third step is the full development phase which includes building the complete AR visualization, integrating the API, processing data, and creating the interactive bubble system. The user interface for displaying detailed pollutant information it is also developed. The penultimate step is the testing and refinement. Extensive testing is conducted to identify and fix bugs and performance issues. User feedback is gathered to make necessary adjustments and improvements to the app. At the end the final step involves launching the APP GeoAIr on relevant platforms (iOS and Android) and providing ongoing support and updates based on user feedback. This step ensures that the APP GeoAIr remains functional and relevant to users.

6. Discussion

The limitations and potential improvements of the Web application prototype relies on the nearest sensor, leading to potentially inaccurate data between sensors, the limit to air quality index (AQI) from a single source, the lacks detailed explanations of data and pollutants.

Faced with these limits, we want to make some improvements for the future developments:

- Data interpolation: use of the data from multiple sensors to create a more precise air quality map (e.g. interpolating or averaging data from nearby sensors)
- City comparisons: make to enable the users to compare AQI and potentially other environmental factors between cities, describing the data used beyond AQI (e.g., pollution types, environmental policies).
- Intra-city comparisons: provide a color-coded 2D map to visualize air quality variations within a city.
- Information expansion: offer detailed explanations of AQI, pollutants, and potentially health risks.
- User Interface (UI): integrate the additional information (data explanations, health risks) into Web application's UI to ensure it remains user-friendly.

7. Conclusion

The challenges of air quality monitoring and the role of citizen awareness in tackling them are many. The limits for air quality data are many too, for example the traditional monitoring stations are expensive and provide limited data on specific locations. It is important the personal awareness, to understand the individual exposure to pollution can encourage behavioral changes. The mobile air quality monitoring based on smartphone and APPs offer a promising solution for personal air quality index (AQI). It will be good for social impact: mobile APPs should educate users and encourage feedback to improve strategies.

These considerations are intimately connected to the European digitization plan, which includes some topics in particular

Extended Reality and Artificial Intelligence with the purpose to contribute to cleaner ambient air, a key deliverable of the EU's Green Deal.

Summarizing some details in conclusion we can briefly mention the use of WebXR and WebGL for scene creation and rendering, emphasizing markerless AR for broader accessibility and the positive feedback from the limited survey regarding user enjoyment and the effectiveness of interactive visualization. Some additional points might give a well-rounded conclusion: data interpolation, city comparisons, information expansion. Finally, we would like to mention the potential broader impact of our project beyond user awareness (e.g., citizen engagement in environmental initiatives).

This approach will provide users and final decision makers with an innovative virtual, realistic, and safe "eXtended" environment in which to experience updated data in near real-time.

As future enhancement there will be the possibility to include visualizations for other pollutants such as CO2 and O3. This would provide users with a more comprehensive understanding of air quality. The APP could implement push notifications to alert users about significant changes in air quality, helping them stay informed and take necessary precautions. It can be possible to allow users to view historical air quality data for their location in order to make them enable to track trends and make informed decisions about their environment. At the can be also interesting to make users enable to share air quality data and insights with a community could foster a sense of shared responsibility and awareness about environmental health.

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