

Democratizing Digital Solutions to Improve Public Health and Urban Air Quality

Contributors: Edmund Seto, Miriam Berhane Russom, Michael Mattmiller, Vaishnavi Ranganathan, Kate Brown, Pietro Vannucci, Alex Mariakakis, Eric Basha, Shahana Khurshid

I. Problem statement

More than half of world's population lives in urban areas, and it is estimated that by 2030 one in every three persons will live in cities with at least half a million inhabitants. Already, there are 31 "megacities", with each one home to over 10 million people [1].

As cities and their population grow across the world, various public health challenges emerge, which are broad and all-encompassing. The World Health Organization defines Health as "*a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity.* [2]" Therefore, public health improvements must consider social conditions, environmental quality, energy, transportation and access, housing and living conditions, equity, sustainability, safety, governance, economic opportunities, diet, exercise, stress, and other lifestyle factors, and infectious and non-infectious diseases, injuries, and mortality – to name a few. Many of these issues are interlinked leading to a complex set of public health challenges that need solving. There is an ongoing need for solutions to these challenges to achieve urban futures that proactively improve the public health of city inhabitants.

Improvements to environmental quality may play a large role in promoting better public health. A 2009 study of environmental effects on public health identified that air pollution significantly affects public health in cities across the world [3]. It is estimated that as much as 23% of the global burden of disease is due to poor environmental conditions [4], and ambient air pollution specifically is the 5th leading risk factor for death, and is responsible for 4.2 million deaths [5].

Because of the importance of ambient air to public health, it is important to have a basic understanding of the sources of air pollution and how it is managed. **Ambient air** is a mixture made up of gaseous, liquid vapor, volatiles, and particle components. While some components of ambient air are naturally occurring, a portion is the result of pollutant emissions from industrial, mobile (e.g., planes, trains, and automobiles), residential, and other human activities. Air pollutants may be transported and modified in the atmosphere.

In many countries, **health-protective standards** exist and air quality is managed by environmental agencies. For example, within the United States, the Environmental Protection Agency, and related state and regional agencies regulate air quality under the Clean Air Act, which requires National Ambient Air Quality Standards (NAAQS) to be set for air pollution. The NAAQS specifies standard air quality levels for 6 Criteria Air Pollutants (Carbon Monoxide (CO),

Lead (Pb), Nitrogen Dioxide (NO₂), Ozone (O₃), Particle Pollution (PM_{2.5} and PM₁₀), and Sulfur Dioxide (SO₂) [6]. Additionally, environmental agencies can establish rules that govern or affect pollutant emissions at their source (e.g., US CAFE standards for vehicle fuel efficiency, and the permitting process for pollutant emissions from industrial facilities).

With the establishment of standards, there is the need to **monitor air quality** to determine if the standards are being met, which again is the responsibility of governmental environmental agencies. Conventional air quality monitoring, however tends to be quite sparse. There are approximately 4000 sites operated by US EPA [7], and so there are many neighborhoods, towns, and cities that do not have any governmental air quality monitoring data.

Despite the dearth of air monitoring data, there has been considerable research into the relationship between **air pollution, human health, and social and economic costs** [3]. Exposure to air pollution can cause damage to the airways through several mechanisms including oxidative stress, airway remodeling, inflammatory pathways, and by enhancing respiratory sensitization to allergens [8]. Exposure to pollutants such as ozone, nitrogen dioxide, and PM_{2.5} can induce airway inflammation. There is strong evidence for the associations between high levels of certain pollutants and health concerns like all-cause mortality and both adverse respiratory (bronchitis, asthma [9-11]) as well as cardiovascular health effects. For example, an increase of 10 µg/m³ in PM_{2.5} has been associated with a 24% increase in the risk of a cardiovascular event and 76% increase in the risk of death from cardiovascular disease in a group of over 1800 women. [12] New research continues to find other potential relationships, e.g., emerging evidence supports the associations between certain air pollution exposures and adverse birth outcomes, obesity, cognitive disorders and metabolic disease, as well as aging and Alzheimer's disease [13-15]. But there is still a lot that we do not understand about the mechanisms by which air pollution causes and exacerbates certain diseases.

Moreover, existing research has documented that air pollution disproportionately affects certain populations within communities more than others [16]. There may be many potential causes of this, which include structural racism, historical redlining, and other factors, which has resulted in some communities experiencing higher levels of air pollution than others, and thus **environmental justice** problems. Also, certain individuals may be more **susceptible** to adverse health effects from air pollution exposures. For example, children with asthma, individuals with chronic obstructive pulmonary disease (COPD), and individuals with cardiovascular disease are all at higher risk of disease complications when they are exposed to air pollution. In the context of the current COVID-19 pandemic, a study by Harvard researchers identified a strong correlation between long-term exposure to air pollution and mortality rates. The study suggests a 1 µg/m³ increase in PM_{2.5} correlates with an 8% increase in COVID-19 death rate [17]. This is associated with the development of respiratory conditions, like COPD, which are known to increase vulnerability in a person infected with SARS-CoV-2. Also, some may be more **vulnerable** to air pollution and its health effects, such as those who lack insurance or are underinsured, or those that also face other public health threats, including other pollution exposures or have barriers that prevent them from adopting health lifestyles [18].

Within urban contexts, **other civic agencies** beside environmental agencies play an important role in influencing air pollution. For example, land use planning agencies manage zoning and siting decisions that potentially affect the proximity of industrial air pollution sources to residents. Transportation agencies manage policies and plans that affect transport options, routing, and pricing, which affect pollutant emissions. Public health agencies are responsible for population health broadly, and thus are concerned with exposures to air pollution and their

resulting health impacts. Also, non-governmental environmental organizations play an important role in advocating for environmental quality and justice, and often represent the voices of community residents concerned about environmental health impacts. These are just a few examples of some important air quality stakeholders.

As described above, urban air pollution is a complex issue. But, despite the potential for many stakeholders to be involved in the solution, standards and other policy matters to address air pollution problems, there still remain numerous knowledge gaps and opportunities for information technology to play an important role in developing novel and effective solutions to urban public health issues. We are especially interested in the emerging trend towards **democratization of air quality solutions**, which involves the following:

- (1) More widespread scalable air quality data collection,
- (2) Open and easy access to data for city agencies and citizens,
- (3) New information services, and tools to collect feedback from urban inhabitants,
- (4) Engagement of urban residents and air quality stakeholders in developing equitable and health-promoting solutions to reduce air pollution, and
- (5) Equitable interventions and regulations from the city agencies.

The rest of this paper will elaborate on implementing strategies to achieve democratized air quality solutions that can help address major public health concerns.

II. A movement towards democratized air quality: case studies

While the aforementioned air quality framework has existed for decades in the US since the establishment of the Clean Air Act of 1963, in recent years, we have observed tremendous innovation aimed at addressing the short-comings of a top-down, largely government-led and operated effort. As described in the cases below, innovation has occurred through the nexus of technologies, including the availability of lower-cost yet well-performing air quality sensors, mobile technologies, Internet of Things (IoT), and cloud computing, as well as new paradigms for collecting and acting on data, such as with Smart Cities, community-engaged research, and citizen (or participatory) science.

Case Study 1. Smart Inhaler

Asthmatics are susceptible to air pollution exposures because they have the potential to exacerbate respiratory symptoms. Air Louisville is a collaborative project among public, private, and philanthropic organizations to address the high adult asthma prevalence in Louisville, Kentucky [19]. They used an FDA-approved medication inhaler sensor developed by Propeller Health that connects with a smartphone app to track when, where and how often users experience asthma symptoms. The data combine with a personalized asthma management approach to help patients better manage their symptoms. The inhaler does not include air

pollution sensing per se, but because use of the inhaler may be correlated with exposure to poor air quality, the locations of inhaler use tracked by the app, may provide insights to city leaders on air pollution issues (Figure 1).

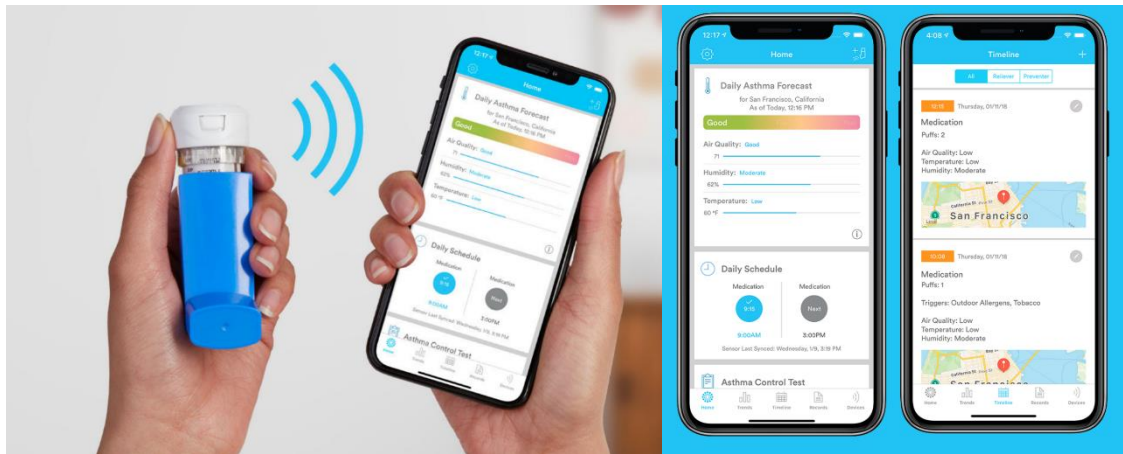


Figure 1. Example screens from Propeller Health's website.

Case Study 2. Purple Air and Weather Underground

What started out as a grassroots effort by an engineer who wanted to better understand his own neighborhood air quality resulted in the development of the Purple Air sensor, a low-cost particle sensor connected to a simple IoT-capable microcontroller that transmits particle concentration measurements to a cloud where the data could be visualized on a map (Figure 2) [20]. The system has become quite popular, and has been adopted by Weather Underground, which collates weather measurements collected by citizen scientists who set up their own weather stations [21].

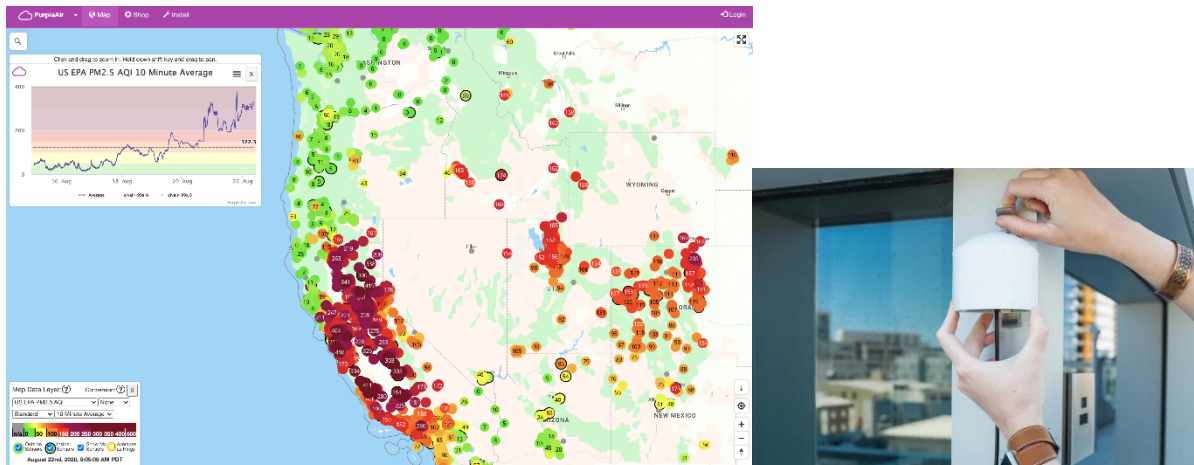


Figure 2. Example of screen capture of Purple Air's website map during the 2020 Northern California Fire Complex, and an image of the Purple Air monitor from their website.

Case study 3: Local Government Initiatives

While the responsibilities related to air quality policy, enforcement, education or advocacy varies from jurisdiction to jurisdiction, country to country, many stakeholders in the government, academia and non-profit sectors would benefit from the ability to get more information and insight regarding air quality. This is especially true when the enhanced air quality data can be analyzed with other data sets that could include health, social, economic, etc. to determine corollary or causal relationships. Examples of initiatives that have been funded by local governmental agencies that analyze air quality include IMEC's site for fine-grained real-time air quality monitoring (Figure 3) [22] and The Chicago Health Atlas [23] created by the CityTech Collaborative. These are examples of tools that enable users to analyze datasets related to specific areas related to air quality that can lead to actionable insights. Additional examples include the road use toll in UK and Singapore (plan for taxing detrimental activity and rewarding beneficial activity), and congestion pricing in Seattle [24].



Figure 3. Screen capture from IMEC's website of fine-grained real-time air quality map that acts as a digital twin to support smart city policies.

III. Possible New Case Studies to Explore

With the availability of granular and scalable air quality sensing enabled by IoT, the collection and sharing of data becomes more feasible. What remains is to increase air-quality awareness among the city residents and incentivize them to act on the knowledge. A study on coupling measurements and experiences to create a narrative that makes the invisible air pollution visible to people sheds light on how such awareness can be created [25]. Building awareness needs cooperation between city agencies and its residents; where the city can make quantitative data available to the public and educate them, and the qualitative feedback from residents can help identify pollution sources and take actions to mitigate them. Most relevant to public health is feedback from the public on the impacts of air pollution on their daily lives, and especially how air pollution affects their health and well-being.

How does this improve Public Health? By enabling residents access to hyperlocal air quality data and empowering them to voice their concerns about air pollution exposures this will drive civic action towards reducing sources and emissions of air pollutants in the community, lead to sharing of strategies in which people may reduce their own personal exposures, and building awareness of air pollution related health effects and ways to avoid these health effects. Thereby, public health may be improved at any point along the continuum:

Policy/Planning → Pollution Sources → Emissions → Air Quality → Exposures → Health Outcomes



Figure 4. Workshop from Project Eclipse to study public perception of environment and air quality to create awareness based on objective measurements and subjective experiences [25] (Top). Creating community awareness and interactive participation: use simple technology like QR codes for citizens to learn about air quality and contribute to creating a city-wide Air Quality perception map (Bottom).

Community Awareness and Citizen Feedback

The aforementioned case studies demonstrate that individuals are willing and able to engage in participatory sensing provided some combination of two key characteristics of the system:

- (1) the system has a low barrier to entry, or
- (2) individuals are aware of the target issue and motivated enough to do something about it.

Although there are many public sources of air quality information (e.g., websites, news reports), people who live in communities with consistently poor air quality are more likely to be aware of air quality issues than people in communities with generally clean air [26]. Therefore, awareness cannot be taken for granted.

We believe that the first step needs to be a low-barrier method for providing people with information about air quality, thereby raising awareness about air quality issues. With that in mind, we envision a world where air quality sensors are deployed throughout a city on everyday landmarks—lampposts, bus stops, intersections, etc. Although these sensors may be hidden from people’s views, people would be able to “see” information derived from the sensors through TV, radio news, or other media communications similar to how the weather is routinely reported. Information may be provided in more of a real-time manner as well through e.g., digital signage. Yet there are potentially more engaging ways for the public to interface with sensor data. For example, in public places, a nearby QR code with a short message could entice residents to engage with the sensors. The user audiences for the messaging could include:

- **People with respiratory issues:** “Do you have respiratory issues? Scan this code to protect yourselves from poor air quality!”
- **Younger students:** “Want to learn more about the air around you? Scan this code to learn how to reduce air pollution!”
- **Concerned citizens near local polluters:** “Are you concerned about the air quality in your neighborhood? Scan this code to take action!”

One of the goals is to create opportunities for meaningful engagement between people and their environmental quality, in ways that are empowering rather than disempowering. For example, anyone who scans the QR code would instantly be taken to a website that shows the nearby sensor’s data. The data would be summarized in a way that is easy to digest, showing trends of the data over time and providing human-readable interpretations of the data. The site may also allow them to voice their concerns, as well as see others’ similar concerns, and possibly to offer potential solutions.

We believe this mode of interaction is more enticing than past suggestions for democratized sensing—namely approaches that ask individuals to carry a sensor with them or to download an app [27]—because QR codes are a familiar interaction that people can do with relatively minor initial investment, though we acknowledge that not everyone has access to digital devices or networking.

By scanning the QR code, people can begin to engage with air quality data that is more meaningful than existing data sources because of its hyper-locality and convenience. Some individuals may only consume the data as the complete extent of their engagement; however, we are hopeful that a subset of individuals would be motivated enough to feel the need to voice their concern based on their observations. For these individuals, the website would provide a link to a brief anonymous survey. The survey could include targeted questions about the person’s health (e.g., “Do you have a respiratory condition that you think is impacted by this air quality?”), but would mainly provide a place for them to voice their concerns. Again, the amount of effort required to get to this survey is very minimal since it does not require a dedicated device, an app installation, or a login.

Social Innovation for Air Quality Reporting

With increasing attention to global climate change, health risks and their link to poor air quality, more people across the world are becoming aware of the need for clean air. However, not everyone is incentivized to carry a sensing device as we have seen so far. As the cities dedicate more resources to the sensing and sharing air quality data, there comes a need to have residents participate and play a larger role in providing appropriate feedback and adopting measures for cleaner air. We propose leveraging crowdsourcing and social innovation as a means to spread awareness and gather public feedback. Social approaches are often more successful in achieving goals in a way that is beneficial to most of the stakeholders [28]. Social cognitive studies show that social networks provide an illusion of enhanced control which is directly related to progress, in contrast to the feeling of a lack of control when individuals act alone towards a bigger cause [29]. We have seen analogues for such effective social innovation with travel apps like trip advisor, Google maps, neighborhood crime watch and biodiversity reporting apps like iNaturalist [30]. Applying this towards air quality, we propose a social app that can be used by residents to learn and share information about the air quality and their experiences on a regular basis. The following can be enabled for users and cities with an app:

- Individual benefit: With provisions for security and privacy-protection, a user can add their symptom information (e.g., asthma, COPD symptoms), triggers and log areas and times which are known to cause them distress. The app can act as an information journal that logs air quality related health observations and help the user take appropriate measures along the lines of a personalized environmental health assistant.
- Social benefit: A user can see shared observations from other residents with similar health conditions and up vote/down vote the observation based on their own experience. Frequently voted areas of distress can be flagged for a city's attention. The sensitive or general users can use the app to navigate their way with least distress in terms of air quality. With a social contribution, air quality perception information can easily become available on a global scale, so that the users are aware even while traveling.

This qualitative data would be used to augment existing datasets that are available to local government officials, emphasizing areas of key concern or providing additional context to the data itself. With this combination of crowdsourced qualitative observations and granular quantitative sensor data, cities can make learned decisions towards budgeting and prioritizing their air quality improvement measures and help their citizens address their concerns. Moreover, the qualitative data when assisted with additional information, such as images of the environment or tags (like activity, traffic, idling vehicles, smoking area), can give context to the sensor data events, which otherwise lack context and might seem noisy.

In a way, this ecosystem would also function similarly to how Yelp reviews provide additional information to local officials about restaurants. Health inspectors review restaurants' health and safety practices on a yearly basis; however, individuals can voice their concerns throughout the year through Yelp. If a particular restaurant neglects best practices and individuals comment on those behaviors in their reviews, that can be enough impetus to have a health inspector investigate further. Similarly, individuals can raise their concerns about the air quality in a particular location with the context of their observations and health needs. If enough people raise concern about how air quality is impacting their health, we believe that feedback can expedite action from local governments.

IV. Data or research needed to address the problem

We foresee that our envisioned system could incorporate data from three different sources:

- (1) local quantitative sensors,
- (2) public government datasets like the EPA measurements, and
- (3) qualitative feedback from individuals.

We provide examples for each of these categories below:

Local Quantitative Datasets

The foundation of our system lies in the availability of hyperlocal air quality sensor data that can be made available to individuals. We foresee that Microsoft's Project Eclipse [31] is a prime candidate for this purpose. The Eclipse sensor includes sensors for multiple air gases (CO, NO₂, SO₂, and O₃), particulate matter (PM₁, PM_{2.5}, and PM₁₀), local weather (temperature, humidity), and location. These sensors are free of infrastructure dependencies, operate on harvested solar energy and talk directly to the cloud using LTE-m cellular connectivity. This makes the sensors inexpensive and easy to deploy on structures like lampposts with a simple zip-tie, thus making them easy for cities to adopt.

However, there are other sensor streams that could be informative to end-users. Motivated by the rising interest in the surveillance of infectious diseases, researchers are actively developing ambient cough and respiratory symptom monitors [32-34]. Cough monitors can be deployed on an individual's smartphone to track their own coughing behaviors, but they can also be deployed within a local environment to estimate the local prevalence of respiratory issues.

Public Datasets

There is a wide assortment of public datasets that could provide context to air quality observations. For our proposed system, we foresee three domains of particular interest:

1. **Urban planning:** Air quality and air pollution exposures are heavily influenced by land zoning [35-36], so knowing the distribution of factories, businesses, and residential areas, and locations of sensitive populations e.g., schools, throughout the city would be particularly helpful. Populations are rarely static, so air pollution can also move according to different modes of transportation. A bus moving past an air quality sensor may temporarily spike a sensor's readings, so correlating that sensor data with bus schedules could explain such shifts in the data. Similar reasoning could be applied to traffic data and event schedules for major venues. As people travel and congregate to a particular location for a sports event or concert, the sudden migration of hundreds of cars can explain drops in air quality on particular days.
2. **Weather and geography:** Several weather patterns can result in the deterioration of air quality. Wind patterns can carry pollutants across a region. Topography can create conditions that trap pollutants, with a well-known example being the various valleys in

and around Los Angeles. Temperature inversion can also trap pollutants by stagnating the potential for air flow for hours or days at a time.

3. **Health:** Although we may be able to have individuals self-report respiratory issues and other ailments that could be exacerbated by poor air quality, public datasets can provide coarser information with less threat to people's privacy. Knowing the prevalence of ailments in particular neighborhoods or clinics could provide clues into where people at great risk reside. It is possible to link data from vital records (birth and death outcomes), disease surveillance and disease registries, and hospital and pharmacy records to air quality data, which can enable further research into the associations between air pollution and health outcomes, as well as help cities better quantify the health and economic burdens of air pollution.
4. **Census and equity:** Publicly available census datasets, such as those in the US from the decennial census and American Communities Survey [37] are a rich source of information for allocating resources within a city. If the air pollution mitigation steps are to be fair and equitable, the distribution of population and their resource requirements should be weighed in correctly. For instance, more crowded regions of a city need better public transportation infrastructure to connect its larger populations. An example is the Equity plan 2025 from the City of Tacoma, WA, which takes a data-driven approach towards urbanization and resource planning based on mapped equity data [38]. Another example of an equity tool that combines census data and air pollution data is a state-wide Environmental Health Disparities Map produced by combining indicators of socioeconomic conditions and environmental quality for Washington State [39-40].

Local Qualitative Datasets

While numerous efforts have explored the combination of quantitative data from public resources and individuals, we feel that the incorporation of qualitative feedback from individuals has been underexplored, particularly those that allow for simultaneous visualization, exploration and analysis, and fostering of improved understand qualitative and quantitative data in interactive ways with others in the community. Individuals can often fill in gaps that are overlooked by local governments, particularly neglected parts of a city that may not always get the same attention as others. We imagine that individuals can contribute personal qualitative data to either support or augment existing quantitative datasets by reporting local traffic patterns and related observations. Individuals can also provide anecdotes about their experiences pertaining to air quality as we have seen so far.

Data Security and Privacy Considerations

Datasets that are available either from public resources, or data that are self-reported by individuals, typically contain personal identifiers or details that can lead to identity associations. Repeated cases where such personal data has been used, without user consent, by private or public agencies have created situations where people may be reluctant to share any information at all. This is more so when it concerns personal health and preference data. While most public records take steps to anonymize the datasets they hold, any other mode of acquiring information must ensure privacy preserving policies. Privacy concern is an important aspect to overcome to truly create a low barrier to entry and encourage participation and contribution from individuals. Starting from the technology required to gather the individual's

data, to storage, processing and sharing the information with the community or the public officials, there needs to be a standard established to maintain anonymity.

Research Needs

With the development and deployment of the aforementioned social feedback app for air quality, there are numerous research questions that could be potentially explored. Below we list some important questions:

1. What are the best ways to encourage participation? What are the perceived costs/benefits for those that participate?
2. What are the characteristics of participants? Is participation equitable, e.g., participation from all neighborhoods and people of different ages, race/ethnicities, and income levels, and levels of digital literacy?
3. What are the benefits to different city governmental agencies? For example, how might a transportation agency benefit from responses from residents? How might a public health department benefit?
4. What privacy concerns are there with the system? What are best practices and standards to address these concerns?
5. How might health researchers learn more about the many possible health effects related to air pollution by comparing user feedback with sensor data?
6. Can we learn more about who is most vulnerable to air pollution exposures in a community?
7. Is it possible to utilize user feedback to better manage or intervene on air pollution? For example, can users find ways to avoid exposures? Can the city better identify air pollution violations to reduce emissions?
8. Is it possible to model and/or simulate urban changes and their impacts on air quality and public health?

V. Stakeholders, Services Needed and Expertise to Analyze Data

Having so far seen how air quality relates to public health we have discussed some ways to democratize the measurement of air quality, both qualitative and quantitative. The general question that comes next is “How can air pollution data inform city-level interventions that would improve health?”. Being able to transform insights into action will ultimately be the way we can truly affect change and improve public health as it relates to air pollution.

Stakeholders

Better data quality will help stakeholders concerned with air quality affect change and drive better environmental, health and social outcomes. While the responsibilities related to air quality policy, enforcement, education or advocacy varies from jurisdiction to jurisdiction, country to country—many stakeholders in the government, academia and non-profit sectors would benefit from the ability to get more information and insight regarding air quality. This is especially true when the hyperlocal air quality data can be analyzed with other datasets

including those related to health, social, or economic conditions to determine corollary or causal relationships. We have already mentioned examples, such as efforts by IMEC and Chicago Health Atlas and the Washington Environmental Health Disparities Map, that are beginning to realize this vision of engaging various stakeholders around a theme of air quality and environmental conditions generally. These are examples of tools that enable users to analyze datasets related to specific areas related to air quality that can lead to actionable insights.

- **Governmental Public Health agencies** have the mandate to promote and protect public health for all, including pollution-related health issues. They also conduct education and outreach to communities in their jurisdictions. Public health entities have a lens of promoting social and health equity and educating the public they serve. These government entities sometimes establish policy, monitor air quality, or enforce laws related to air quality.
- **Government Environmental and Ecological agencies** are tasked with protecting the environment. These government entities are most often charged with monitoring air quality and often responsible for enforcing air quality laws and policies. As with public health entities the specific responsibilities related to policy and enforcement vary from region to region. They are reliant on data to carry out their mandate to ensure air quality for their constituents.
- **Academic Public Health** entities are often on the cutting edge of research related to the effects of air pollution on health. These organizations often provide the evidence that sways public opinion and informs policy through rigorous research methodology.
- **Clean Air Advocates** are almost always non-governmental organizations and can include environmental non-profits such as the Sierra Club, health related non-profits such as the American Lung Association or the European Federation of Clean Air and Environmental Protection Associations (EFCA), as well as more local/regional environmental justice organizations. These groups can mobilize their membership to exert political pressure on elected officials and often have lobbying functions to inform policy to promote clean air.
- **Government policy makers** at the local, regional or national level are typically elected officials in executive, legislative or parliamentary roles who are chartered with forming policies and passing laws related to air quality. Per above, the enhanced air quality information made available directly to these government officials combined with the outcomes and efforts from the stakeholder groups above could have a profound impact on everything from air quality laws to urban planning, transportation policy and areas related to everything from public health to social equity.
- Finally, at **the grassroots level, individual community leaders, active residents, school teachers, religious leaders, and others** can all play important roles in organizing their communities to better utilize air quality information technologies.

Services needed

To enable decision making for different stakeholders we need to design for a hyper-scalable system that is capable of hyperlocal data collection, analytics, and enable a rich ecosystem of tools. Key services and capabilities include:

- Ability to ingest data from hyperlocal low-cost air quality devices enabled through IoT.
- Data analytics and correlation with other data sources (public datasets and local qualitative datasets), algorithms to correlate between air quality and effects on public health.
- Digital twin representation of the spaces including “what if” simulation in support of urban planning.
- Visualization tools to provide context driven “pane of glass” for decision making.
- Apps for public engagement both to provide insights into air quality residents are exposed to, their neighborhood, and along their commute route, as well for community members to contribute qualitative data.
- Open data and data sharing between different communities, cities, and regions.

The role of Digital Twins and City planning

Digital Twins technology has entered the realm of smart cities and can enable urban planners make better decisions with the help of data integration and visualization from across the urban space. A city digital twins would represent a digital replica of buildings, streets, parks, traffic, noise and air quality levels and more. Urban planners have already been using 2D and 3D models and computer aided design for years, however the integration of real time sensor data enabled by IoT devices, location data, weather data, traffic data, people movement data is what is a game changer for urban planning and policy making. Technologies like the Microsoft’s Azure Digital Twins [41] enables the modeling and digital representations of connected environments like buildings, factories, farms, energy networks, railways, stadiums and cities, and bring these digital twins to life with a live execution environment and integration of IoT data to ultimately unlock powerful insights. These digital representations can be utilized to simulate the impact of any changes to the environment. For example, Digital Twins may be used to answer:

- How does air quality change when changing a street into a pedestrian area?
- Would the air quality improve by transforming an unused urban space into a park?
- What happens when reducing highway traffic?
- Would the air pollution simply move to another part of the city?

These are all examples of planning and policy questions and decisions that can be enabled via digital twins, simulation, and taking into account multiple variables at play, the urban fabric and the citizens. Moreover, digital twin analyses may be particularly powerful when driven by the community input and feedback from the engagement app, QR codes, etc. described above.

Expertise required to analyze data

The availability of different data sources also calls for skills to correctly analyze them and draw inferences that can address air quality issues. Tasks needed for data analysis:

- Processing air quality data – making sense of emission events and temporal/spatial evolution of pollution
- Using Innovation and technology to relay, collect and document relevant information to/from the people

- Interpreting public sentiment/crowdsourced physical reactions and matching it with air quality events in time and space
- Linking other data from various fields (e.g., transportation, health, etc.)
- Developing incentive structures around air quality improvement and exposure reduction measures
- Designing and evaluating interventions for individuals as well as a city

Ethics and Air Quality Equity considerations

Given the potential for bias in AI algorithms and data sets and urban planning decision making, and the harm and inequity which can result [42], it will be crucial to create fair algorithms and to focus the use of data to create services which can enable a more equitable future for urban life. To reduce the potential for biases, we propose to engage diverse publics in the implementation of research, and especially the design of data analyses and interpretation of the findings. Therefore, we propose to identify experts with domain knowledge needed to effectively collect and analyze data for this research. This may include experts in air pollution and public health sciences, sensing, systems, user interaction design, data visualization, mapping, community-engagement, as well as local civic and community leaders and stakeholders.

VI. Conclusion and Next Steps

There is sufficient interest to take next steps towards this research. We identified the following next steps:

1. Develop detailed requirements necessary to address the key research needs.
2. Identify relevant expertise and form teams to contribute to specific research project tasks.
3. Identify potential cities for pilot projects.
4. Develop specific proposals with well-defined outcomes and research goals for city pilot projects.
5. With diverse air quality stakeholders, implement and evaluate city pilot projects.
6. Evaluate lessons learned across the pilot projects to identify opportunities/barriers to scaling up from pilot projects to larger scale sustainable implementations.

I. References

[1] United Nations, Department of Economic and Social Affairs, Population Division, The World's Cities in 2016 - Data Booklet (ST/ESA/SER.A/392), 2016. Available: https://www.un.org/en/development/desa/population/publications/pdf/urbanization/the_worlds_cities_in_2016_data_booklet.pdf

- [2] Preamble to the Constitution of WHO as adopted by the International Health Conference, New York, 19 June - 22 July 1946; signed on 22 July 1946 by the representatives of 61 States (Official Records of WHO, no. 2, p. 100).
- [3] K. Remoundou and P. Koundouri, "Environmental Effects on Public Health and Economic Perspective," *Int J Environ Res Public Health*, 6(8), pp. 2160-2178, 2009.
- [4] World Health Organization, Global Health Observatory (GHO) data. Accessed on Sep 25, 2020. Available: <https://www.who.int/gho/phe/en/#:~:text=Public%20health%20and%20environment&text=When%20accounting%20for%20both%20death,if%20environmental%20risks%20were%20removed.>
- [5] S. Tong, "Air pollution and disease burden", *The Lancet Planetary Health*, 3(2), E49-E50. 2019.
- [6] United States Environmental Protection Agency, NAAQS Table. Accessed on Sep 25, 2020. Available: <https://www.epa.gov/criteria-air-pollutants/naaqs-table>
- [7] United States Environmental Protection Agency, Outdoor Air Quality Data. Accessed Sep 25, 2020. Available: [https://www.epa.gov/outdoor-air-quality-data/air-data-basic-information#:~:text=Monitoring%20Data%20%2D%20Ambient%20\(outdoor\),AQ%20\(Air%20Quality%20System\).](https://www.epa.gov/outdoor-air-quality-data/air-data-basic-information#:~:text=Monitoring%20Data%20%2D%20Ambient%20(outdoor),AQ%20(Air%20Quality%20System).)
- [8] M. Guarnieri and J.R. Balmes, "Outdoor air pollution and asthma", *Lancet*, 383(9928): pp. 1581-1592, 2014.
- [9] N. Künzli, R. Kaiser, S. Medina, M. Studnicka, O. Chanel, P. Filliger, M. Herry, F. Horak Jr, V. Puybonnieux-Texier, P. Quénel, and J. Schneider, "Public-health impact of outdoor and traffic-related air pollution: a European assessment." *The Lancet*, 356(9232), pp.795-801, 2000.
- [10] J. McCreanor, P. Cullinan, M.J. Nieuwenhuijsen, J. Stewart-Evans, E. Malliarou, L. Jarup, R. Harrington, M. Svartengren, I.K. Han, P. Ohman-Strickland, and K.F. Chung. "Respiratory effects of exposure to diesel traffic in persons with asthma". *New England Journal of Medicine*, 357(23), pp.2348-2358. 2007.
- [11] M. Brauer, G. Hoek, H.A. Smit, J.C. De Jongste, J. Gerritsen, D.S. Postma, M. Kerkhof, and B. Brunekreef. "Air pollution and development of asthma, allergy and infections in a birth cohort." *European Respiratory Journal*, 29(5), pp.879-888, 2007.
- [12] K.A. Miller, D.S. Siscovick, L. Sheppard, K. Shepherd, J.H. Sullivan, G.L. Anderson, and J.D. Kaufman. "Long-term exposure to air pollution and incidence of cardiovascular events in women." *New England Journal of Medicine*, 356(5), pp.447-458, 2007.
- [13] B. Ritz, M. Wilhelm, K.J. Hoggatt, and J.K.C. Ghosh. "Ambient air pollution and preterm birth in the environment and pregnancy outcomes study at the University of California, Los Angeles." *American journal of epidemiology*, 166(9), pp.1045-1052, 2007.
- [14] N.M. Gatto, V.W. Henderson, H.N. Hodis, J.A.S. John, F. Lurmann, J.C. Chen, and W.J. Mack. "Components of air pollution and cognitive function in middle-aged and older adults in Los Angeles." *Neurotoxicology*, 40, pp.1-7, , 2014.
- [15] J. Schwartz. "Air pollution and children's health." *Pediatrics*, 113(Supplement 3), pp.1037-1043, 2004.
- [16] M.L. Miranda, S.E. Edwards, M.H. Keating, and C.J. Paul, "Making the environmental justice grade: the relative burden of air pollution exposure in the United States." *International journal of environmental research and public health*, 8(6), pp.1755-1771, 2011.
- [17] X. Wu, R.C. Nethery, M.B. Sabath, D. Braun, and F. Dominici, "Air pollution and COVID-19 mortality in the United States: strengths and limitations of an ecological regression analysis." *Science Advances* (in press).
- [18] N.A. Ponce, K.J. Hoggatt, M. Wilhelm, and B. Ritz. "Preterm birth: the interaction of traffic-related air pollution with economic hardship in Los Angeles neighborhoods." *American journal of epidemiology*, 162(2), pp.140-148, 2005.
- [19] Air Louisville, Air Louisville, Accessed Sep 25, 2020. Available: <https://airlouisville.com/>
- [20] PurpleAir, PurpleAir, Accessed Sep 25, 2020. Available: <https://www2.purpleair.com/>

- [21] Weather Underground, We Need Your Help to Fight Air Pollution, Accessed Sep 25, 2020. Available: <https://www.wunderground.com/sensors/purpleair>
- [22] IMEC, Technology for real-time air quality monitoring, Accessed Sep 25, 2020. Available: <https://www.imec-int.com/en/sensor-networks-for-iot/technology-for-real-time-air-quality-monitoring>
- [23] Chicago Health Atlas, Chicago Health Atlas - Access health data for Chicago and your community, Accessed Sep 25, 2020. Available: <https://www.chicagohealthatlas.org/>
- [24] J. Cohen, "Tolls to drive in downtown Seattle? New study examines the good and the bad", Crosscut, 2019, Accessed Sep 25, 2020, Available: <https://crosscut.com/2019/05/tolls-drive-downtown-seattle-new-study-examines-good-and-bad>
- [25] S. Liu, J. Cranshaw, A. Roseway, "Making Air Quality Data Meaningful: Coupling Objective Measurement with Subjective Experience through Narration," DIS2020, July 6-10, 2020, Eindhoven, NL.
- [26] M.C. Mirabelli, S. Ebelt, and S. A. Damon, "Air Quality Index and air quality awareness among adults in the United States". Environmental Research, 183, p.109185, 2020.
- [27] C.C. Lim, H. Kim, M.R. Vilcassim, G.D. Thurston, T. Gordon, L.C. Chen, K. Lee, M. Heimbinder, and S. Y. Kim. "Mapping urban air quality using mobile sampling with low-cost sensors and machine learning in Seoul, South Korea." Environment international, 131, p.105022, 2019.
- [28] W. Phillips, E.A. Alexander, and H. Lee. "Going it alone won't work! The relational imperative for social innovation in social enterprises." Journal of Business Ethics, 156(2), pp.315-331, 2019.
- [29] D.M. De Carolis, B.E. Litzky, and K.A. Eddleston, "Why networks enhance the progress of new venture creation: The influence of social capital and cognition." Entrepreneurship theory and practice, 33(2), pp.527-545, 2009.
- [30] iNaturalist, iNaturalist, Accessed Sep 25, 2020. Available: <https://www.inaturalist.org/>
- [31] Microsoft, Project Eclipse, Accessed Sep 25, 2020, Available: <https://www.microsoft.com/en-us/research/project/project-eclipse/>
- [32] S. Matos, S. S. Birring, I. D. Pavord and D. H. Evans, "An Automated System for 24-h Monitoring of Cough Frequency: The Leicester Cough Monitor," in IEEE Transactions on Biomedical Engineering, vol. 54, no. 8, pp. 1472-1479, Aug. 2007.
- [33] X. Sun, Z. Lu, W. Hu, and G. Cao. 2015. SymDetector: detecting sound-related respiratory symptoms using smartphones. In Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing (UbiComp '15). Association for Computing Machinery, New York, NY, USA, 97-108.
- [34] F. Al Hossain, A.A. Lover, G.A. Corey, N.G. Reich, and T. Rahman. 2020. FluSense: A Contactless Syndromic Surveillance Platform for Influenza-Like Illness in Hospital Waiting Areas. Proc. ACM Interact. Mob. Wearable Ubiquitous Technol. 4, 1, Article 1 (March 2020), 28 pages.
- [35] Iowa Department of Natural Resources, "Cleaner Air Better Communities", 2012, Accessed Sep 25, 2020, Available: <https://iwrc.uni.edu/sites/default/files/Land-Use-Planning-for-Air-Quality4-17-12.pdf>
- [36] California Environmental Protection Agency, California Air Resources Board, "Air Quality and Land Use Handbook: A Community Health Perspective", 2005, Accessed Sep 25, 2020, Available: <https://ww3.arb.ca.gov/ch/handbook.pdf>
- [37] United States Census Bureau, Accessed Sep 25, 2020, Available: <https://www.census.gov/>
- [38] City of Tacoma, Washington, "Realizing Equity in Tacoma - Equity Index," Accessed Sep 25, 2020. Available: https://www.cityoftacoma.org/government/city_departments/equity_and_human_rights/equity_index
- [39] E. Min, D. Gruen, D. Banerjee, T. Echeverria, L. Frelander, M. Schmeltz, E. Saganić, M. Piazza, V.E. Galaviz, M. Yost, E.Y.W. Seto, "The Washington State Environmental Health Disparities Map: Development of a Community-Responsive Cumulative Impacts Assessment Tool." Int. J. Environ. Res. Public Health, 16(22), 4470. doi:10.3390/ijerph16224470, 2019.

[40] Washington State Department of Health, "Washington Tracking Network - A source for environmental public health data", Accessed Sep 25, 2020, Available: <https://fortress.wa.gov/doh/wtn/WTNIBL/>

[41] Microsoft Azure, Azure Digital Twins, Accessed Sep 25, 2020, Available: <https://azure.microsoft.com/en-us/services/digital-twins/>

[42] C. O'Neil, "Weapons of Math Destruction - How Big Data Increases Inequality and Threatens Democracy", Penguin, 2017.