OPENAIR: UNLOCKING THE POTENTIAL OF SMART LOW-COST SENSING THROUGH BEST PRACTICE AND HARMONISED CROSS-JURISDICTIONAL DATA SHARING

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Abstract

The intensity and community impact of poor air quality and extreme heat can vary significantly at local scales. Data from state-managed ambient air quality monitoring networks often lacks the spatial and temporal resolution required for an effective response to community needs. Smart low-cost sensing technology supports collection of real-time data by local authorities in locations that are relevant to their constituents and aligned with their own agency. However, there has been little support and guidance regarding the use of these technologies, and no way of sharing data from different systems and jurisdictions in a usable, trusted, or standardised way.

These challenges have been addressed by the Operational Network of Air Quality Impact Resources (OPENAIR) project. OPENAIR developed extensive best practice resources relating to the use of smart sensing technology and the management of air quality data. The project established a community of practice for local government leadership on air quality issues in NSW, through facilitation and support of an active cohort of Council participants. The project also demonstrated a pilot data feed and platform for sharing and harmonising air quality data streams from multiple commercial monitoring systems, which has the potential to scale into state and national public data infrastructure.

This paper provides an overview of project activities and grounds them in a transdisciplinary mix of literature on smart cities, communities of practice, and data sharing. It makes a case for the value and relevance of OPENAIR and discusses its prospective future impact.

Keywords: Low-cost sensing; Smart City; Data sharing; Harmonisation

1. Introduction

Over the past decade, with advances in compact sensing technology and the Internet of Things (IoT), an increasing diversity of smart low-cost sensing devices have become commercially available. The term ‘low-cost’ sensing device refers to products that vary in price from several tens of dollars, to around AUD$10,000 a unit, with corresponding variation in performance and data attributes. These products have enabled a range of accessible new approaches to environmental monitoring that provide near-real-time data at high spatial and temporal resolutions. As the concept of smart cities has matured over the same period, local governments and other place owners concerned with localised air pollution issues have increasingly experimented with these technologies. However, a widely acknowledged and persistent challenge has been the production of data of low or unknown quality and context, which restricts its utility, particularly for use cases where trust, certainty or rigour is important (Buelvas Pérez et al., 2023; Castell et al., 2017; Clements et al., 2017; Giordano et al., 2021; Kumar et al., 2015; McKercher et al., 2017; Morawska et al., 2018).

Despite these challenges, uptake of smart low-cost sensing technologies has been on the rise in Australia and around the world. Many local authorities that invest in these technologies are seeking ways to improve the utility of the data they produce, to support better local impact creation. While improvements to the design and performance of low-cost sensing products are important, there are two other broad areas of consideration that are equally critical for driving improved data utility and were the focus of the Operational Network of Air Quality Impact Resources (OPENAIR) project. The first is methodology, relating to all aspects of data collection using low-cost sensing technologies. Methodology pertains not only to the process that deliver a given quality of data, but also to the applicability of data to a given real-world challenge, which is a product experimental design. The second consideration is data labelling and sharing, to support better shared understanding of data applicability and improved data access and exchange.

OPENAIR was conceived of in response to a survey of local governments in NSW, facilitated by the NSW Smart Sensing Network (NSSN), following the 2019-2020 'Black Summer' bushfires, which caused harmful levels of air pollution across the state. Survey responses highlighted a diversity of localised air pollution concerns, as well as a general need for Councils to better understand these issues and the effective use of new smart monitoring technologies in pursuit of positive impact creation.

OPENAIR, which ran from 2021 to 2023, was a collaborative project led and co-sponsored by the Climate and Atmospheric Science division of the NSW Department of Climate Change, Energy, the Environment, and Water (DCCEEW). The project was jointly funded through the NSW Smart Places Acceleration program, which supported place-based uplift of the NSW smart city sector between 2020 and 2023. OPENAIR was framed as a smart city innovation initiative with an air quality focus. The project was entirely technology agnostic, with a focus on development of shared best practice methodology and improved data sharing solutions.

2. Project methodology

The principal discourse of OPENAIR was a human-centred smart city narrative that has emerged out of more technology-centric smart city practices of last decade. The human-centred smart city positions technology within a broader system of societal, economic and ecological considerations (Khansari et al., 2014; Kummitha & Crutzen, 2017; Nam & Pardo, 2011). This emerging global paradigm of smart city best practice is enshrined in international standards[1], and is closely associated with the social and environmental impact focus of the *United Nations Sustainable Development Goals* (United Nations General Assembly, 2015). As a result, the project adopted a system-level approach to impact creation, grounded in people, place and practice, rather than a narrower focus on monitoring technology.

The University of Technology Sydney (UTS) Institute for Sustainable Futures (ISF) was the research and methodology lead and, in partnership with the NSW Smart Sensing Network (NSSN), coordinated contributions from five universities[2], independent academic contractors and the NSW Government over a 20-month period (2021-2023). Eight workstreams were established: Overall methodology (ISF); Air quality science (ANU); Sensing devices (USYD); Impact and operations (ISF); Digital data infrastructure (UTS Faculty of Engineering and IT); Business plan development (WSU); Institutional development (Sitelines Media); Pilot data feed (NSW DCCEEW). Several 'expert advisors' (including researchers from UNSW and USYD, as well as private consultants) were also engaged for the duration of the project, to assist with content production and to directly support local government participants on specialist topics.

Fourteen local government participants from NSW were recruited from the original pool of survey respondents, with each receiving up to $10,000 of grant cash to support sensing technology procurement or services. Participants were invited to deliver their own smart air quality sensing pilot project as part of a cohort. The aims were to ground OPENAIR outputs in real-world settings, establish live data sources for development of the pilot data feed, and establish a growing community of practice for smart air quality sensing. UTS ISF coordinated bi-weekly seminars and four larger half-day workshops for participants, featuring guest speakers and peer-to-peer knowledge exchange. Several participating Councils dropped out of the program in the first year due to resourcing constraints[3], leaving six that completed pilot projects in 2023.

[1] Examples include: International Organisation for Standardisation's ISO 37106:2018 (*Sustainable cities and communities — Guidance on establishing smart city operating models for sustainable communities*); and ISO 37122:2019 (*Sustainable cities and communities — Indicators for smart cities*).

[2] University of Technology Sydney (UTS), University of Sydney (USYD), Australian National University (ANU), Western Sydney University (WSU), and University of NSW (UNSW)

[3] Explanations included impacts of Covid 19, natural disaster recovery, funding cuts, and staff turnover.

OPENAIR adopted a participative action research (PAR) methodology (Baum et al., 2006), which requires the researcher to situate themselves within a broader participatory, collaborative and iterative process of change-making, alongside other stakeholders, who are themselves positioned as co-researchers. The process produced consensus about best practice and a working method for data exchange, grounded in real-world activities, where a pragmatic solutions-focused approach delivered outputs that were ideally adapted to the needs of participants. The smart city research community has identified PAR as a suitable and effective tool for developing smart city policy (Laenens et al., 2019; Schaffers et al., 2011). van Waart, Mulder, & de Bont (2016) advocate Participatory Design (in the PAR tradition) for improved university engagement with experimental smart city initiatives. Foth and Brynskov (2016) describe PAR as 'a useful and fitting research paradigm to guide methodological considerations surrounding the study, design, development, and evaluation of civic technologies'.

The project generated a wealth of insights, that emerged from PAR practice, with contributions from researchers across all eight workstreams. A discussion paper aimed at the NSW government was produced by NSSN and UTS at the end of the project. This included a series of recommendations for promoting and supporting the use of smart, low-cost air quality sensing, enhancing state government air quality information products and services, enabling improved data sharing, and expanding the OPENAIR approach to other environmental measurements beyond air quality.

3. Best practice resources

OPENAIR best practice resources were developed as a series of 16 fact sheets (concise high-level introductions to key topics), 34 Best Practice Guides (more in-depth step-by-step guides to all aspects of smart air quality monitoring project delivery), and 14 Supplemental Resources (tools and templates, extended compendiums, and related technical materials).

Best practice resources were structured around a framework called the *OPENAIR Impact Planning Cycle* (IPC) (NSW Government, 2023) (Figure 1.), which applies a holistic and transdisciplinary perspective to smart air quality sensing. The IPC provides a framework for establishing desired outcomes and impacts that might be achieved through the targeted utilisation of new data. There are six stages (Table 1.) that step a practitioner through a comprehensive strategic design process in pursuit of this impact. The IPC was developed with reference to a 'logic model' (see appendix B) that forms the core of the NSW *Human services outcomes framework* (Routledge, 2017).

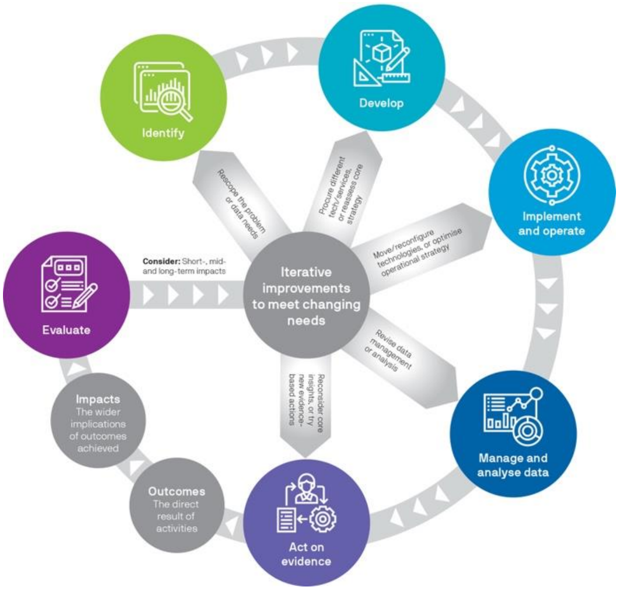

Figure 1. The OPENAIR Impact Planning Cycle

Mirroring the overall PAR methodology of OPENAIR, the IPC is itself a cyclical action research framework that consists of smaller iterative cycles of reflection, action, and learning across each of the six stages. This approach is notably distinct from more traditional linear processes of project delivery commonly found within the local government sector.

Table 1. Stages of the Impact Planning Cycle

IPC Stage	Stage description
Identify	Helps you to establish a project and identify a business case built around a defined problem, stakeholder needs, a strategic objective, and resourcing capacity.
Develop	Guides you through procurement decisions and the design of a sensor network that meets the needs of your business case.
Implement and operate	Guides you through the deployment, testing, commissioning, and operation of a sensor network.
Manage and analyse data	Helps you understand how to interpret, verify, and analyse sensor data to develop actionable insights, and how to manage data to maximise its utility.
Act on evidence	Explains how to leverage data-based insights to support actions that lead to outcomes and impacts.
Evaluate	Guides you through all aspects of project evaluation. Evaluation delivers critical insight into all aspects of the project, supporting iterative improvements across all stages.

By working closely with Councils and real-world technology delivery throughout the project period, researchers were able to design the content and tone of best practice resources to fit the needs of end users. The approach ensured delivery of project outputs with high utility for the local government sector, supporting a strong potential for widespread future uptake and impact creation.

UTS ISF took responsibility for overall editorial control and publication of best practice resources from all workstreams. All outputs were reviewed and approved by NSSN and NSW DCCEEW, before publication on the newly created NSW Air Quality Hub (airquality-hub.seed.nsw.gov.au), hosted within the NSW SEED portal (www.seed.nsw.gov.au).

4. A community of practice

A stated aim of OPENAIR was to establish a community of practice for local government engagement with smart air quality monitoring in NSW. Snyder et al. (2004) identify three core structural dimensions of a CoP: domain, community, and practice. For OPENAIR, the domain was local air quality issues and smart low-cost sensing technology; the community was a product of relationships formed between Council staff through trust building, reciprocity and knowledge exchange; and practice was a combination of the best practice resources generated by the project, and the innovative pilot projects delivered by each Council.

The constructive role of communities of practice in the public sector is well established (Brown & Duguid, 1991, 2001; Hatmaker et al., 2011; Smith, 2016). Smith (2016) highlights the connections made between individuals from different municipalities who work in the same field, noting how this invokes ‘shared language, camaraderie and support when facing similar challenges, exchange of “know how” information, and ultimately, trust’. Of the six Councils that completed pilot projects, four of the lead personnel held environmental sustainability roles and two had current or past roles with a smart city strategy focus (see table 2). A mix of roles and experience in the OPENAIR cohort reflected the transdisciplinary nature of the topic and likely contributed to additional knowledge sharing.

Table 2. Overview of Council participants

Council participant	**Focus and personnel**
Tweed Shire	*Focus:* Resident concerns about particulate pollution under the flight path of Gold Coast Airport *Personnel lead:* Environmental health officer
Muswellbrook Shire	*Focus:* Dust associated with opencast coal mines and associated rail/road transportation in the town of Muswellbrook *Personnel lead:* Sustainability officer
City of Newcastle	*Focus:* Dust associated with the transportation and stockpiling of coal in the residential suburb of Mayfield. *Personnel lead:* Climate change and sustainability manager
Lake Macquarie City	*Focus:* Skills, digital literacy and community trust. Development of a DIY particulate pollution sensing device + community workshops. *Personnel lead:* Fab Lab Lead (formerly smart city lead)
City of Parramatta	*Focus:* CBD air quality, vehicle emissions, street canyon effects. *Personnel lead: Project officer from the City Strategy team*
Sutherland Shire	*Focus:* Smoke from domestic wood heaters in suburban river valleys *Personnel lead:* Senior Environmental Scientist

5. Pilot data feed

Air quality is a transboundary issue, where effective and trusted data sharing is critical for supporting cooperation and systemic solutions. With the rising use of smart low-cost sensing technologies, a growing number of place-owners, including but not limited to local governments, hold potentially valuable data resources. Historical and live-streamed air quality data from low-cost sensor networks is of potential interest to the public, to civil society, to researchers, to other local authorities, and to state government authorities concerned with air quality monitoring or management. The value of this data is inextricably tied to a shared understanding of its fitness for purpose. While much attention has been paid to the absolute quality of data from low-cost sensors with respect to its suitability for application in higher tier data use cases (e.g. supplemental monitoring (Williams et al., 2014)) (Castell et al., 2017), the distinct challenge articulated here relates to data sharing; and in particular, the quality of shared metadata and the data infrastructure that supports it.

Smart air quality sensing devices vary enormously in their performance and the attributes of their output data. It is well established that information about the quality and attributes of data and metadata is a fundamental foundation for trust and informed decision-making about the use and reuse of data (Callahan et al., 2017; Fane et al., 2019; Peng et al., 2021). This information conveys an understanding of ‘fitness for purpose’ (Peng et al., 2021) that is fundamental to effective evidence-based environmental policy-making (Aggestam &

Mangalagiu, 2020) and is arguably vital for supporting systemic impact through the use of smart low-cost air quality monitoring. It means that, when a local government or place owner shares data from a low-cost sensor network, they must provide a standard set of contextual metadata to support its discoverability and useability.

Typically, data from low-cost monitoring networks remains underutilised, both within and beyond the organisation that collects it. Effective utilisation of data relies upon several factors, including the presence of appropriate data policy, standards and best practice, and the strategic positioning and capacity of the prospective data user. However, a core enabler is data sharing infrastructure.

Existing platforms for sharing data from low-cost air quality sensors fall into three categories. The first, which we may call 'opensource community platforms', are tied to a specific model of device, where a user has the option of publishing data from their device to a public platform that hosts all devices of that type within a broader community network. Notable examples of this type of platform include Purple Air (www2.purpleair.com), sensor.community (sensor.community), AirCasting (www.habitatmap.org/aircasting), and Smart Citizen (smartcitizen.me/kits). These platforms tend to align with an explicit ethos of open technology and a variety of opensource tools and APIs are generally available, as well as active global communities of users that provide support. As a result, we do not see this type of data sharing enabled for more proprietary systems, which tend to include the majority of higher performance products within the 'low-cost sensing device' definition.

A second type of air quality data sharing platform, which we may call 'proprietary public platforms', is a bespoke publicly accessible portal tied to a specific proprietary device. These platforms are often commissioned by a place-based client to serve the needs of a particular local initiative and are delivered by a private technology provider. Examples in the Australia and New Zealand context include the Latrobe Valley Information Network (lvin.org), the Christchurch City Council Information Network (cccin.org.nz), and the RAC Air Health Monitor in Western Australia (rac.com.au/about-rac/community-programs/air-health-monitor). This type of platform is restricted to data sharing from a single device type. Accessible metadata is often very limited, it is generally not possible to download historical data, and there tends to be no open API for connection of live streams to third party services.

The final type of commonly accessible air quality data sharing platform is what we may call a 'general open data portal'. Examples in the NSW context include data.gov.au, Data.NSW, and the NSW SEED portal (www.seed.nsw.gov.au). Many local governments also manage their own open data portals and there are several examples of local governments publishing live streamed data from their own low-cost monitoring network via this type of platform. Open data platforms are technology agnostic, meaning that data from any type of device can be shared. They support access and downloading of historical data sets as well as open APIs for live streaming. However, shared data is made available in its original format, and there are no controls on metadata inclusion.

All three types of platform have major limitations and tend to result in shared data with low usability; defined by Attard et al. (2015) in terms of accessibility, interoperability, completeness and discoverability. In the case of general open data portals, data can be difficult for prospective users to discover, and in all three cases data may lack quality control; it may lack clear, standardised and trusted metadata indicators of its quality, completeness and other attributes (Castell et al., 2017); and it will likely be in a format that makes it very difficult to reliably compare or merge it with data from other sources (low interoperability).

OPENAIR aimed to address these usability limitations through development of a pilot data feed system (figure 2.) that ingests live data from multiple different low-cost sensing systems simultaneously. Data arriving in diverse formats is harmonised into a single schema that standardises sensor telemetry (limited for the pilot to temperature, humidity and PM2.5) and metadata from all sources into an interoperable format. An OPENAIR API then makes harmonised data, collected from multiple systems and sources, available to external end points. The OPENAIR pilot data feed is an Extract-Transform-Load (ETL) tool (Vassiliadis & Simitsis, 2009) designed to support distributed real-time low-cost sensing. It sits between data producers and existing end points and solves many of the issues with existing data sharing platforms.

The pilot data feed was developed by NSW DCCEEW and NSSN, with input on the design of the harmonised data schema from ANU and UTS ISF. The feed was established using live data streams from three commonly used commercial low-cost air quality sensing systems (Clarity, Purple Air and AQMesh), operated by four participating Councils.

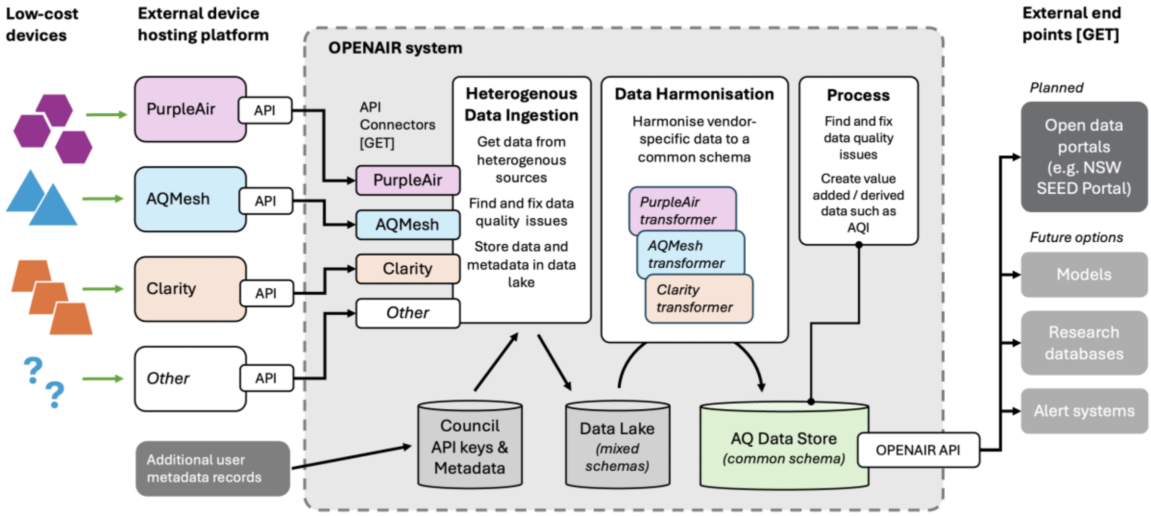

Figure 2. Conceptual diagram of the OPENAIR Pilot Data Flow system

The need for data harmonisation solutions like the OPENAIR pilot data feed is well established in the smart city sector (Bellini et al., 2018; Cirillo et al., 2019; de Castro, 2017; Jara et al., 2017; Ruiz-Alarcon-Quintero, 2016), and more broadly within the fields of spatial and environmental data, where an early milestone was the European INSPIRE Directive (European Parliament, 2007). INSPIRE created an ambitious and comprehensive roadmap for a unified spatial data infrastructure across the EU, with a broad remit that includes air quality in its list of spatial data themes. Along with proceeding EU directives pertaining specifically to the reporting and exchange of ambient air quality information, INSPIRE requires all EU government agencies that produce regulatory ambient air quality data to synchronise their activities and share data in accordance with a common data model (described by Schleidt (2013)). These developments led to initiatives such as the Shared Environmental Information System (SEIS) (European Commission, 2008), and the application of various regional approaches such as the HUMBOLDT Alignment Editor (HALE) ETL tool deployed by the Dutch and Belgian governments (described by Kotsev et al. (2015)). It is noted that the OPENAIR data feed architecture bears similarity to that of HALE and can be viewed as the latest iteration in a line of ETL solutions for air quality data. The critical difference is that the OPENAIR feed is designed for application with data from smart low-cost device networks, which is not accommodated by INSPIRE, SEIS or HALE. Kotsev et al. (2015) noted at the time that such data was too heterogenous and unreliable to tackle in the same way as regulatory air quality data sources. OPENAIR takes on this challenge nearly a decade later, with the added support of best practice design and methodology, a growing community of practice for smart low-cost sensing, and the development of a 'fit-for-purpose' data utility discourse that has elevated the perceived value of low-cost sensor data.

6. Discussion: considering the prospective impact of OPENAIR

OPENAIR is Australia's first and only comprehensive strategic engagement with smart low-cost air quality sensing by a state or territory government. The project has established a growing community of practice within NSW, and a suite of best practice strategies and methodologies that are being informally promoted across Australia through a variety of professional associations, as well as internationally through the C40 Cities Climate Leadership Group (NSW Smart Sensing Network, 2024).

OPENAIR has supported NSW local government participants to plan and deliver well-designed, strategic, and methodologically appropriate projects for data-driven impact. The project's freely accessible best practice resources enable other local governments to follow suit. The hope is that a growing number of smart low-cost sensing networks across NSW and Australia are designed and operated according to this best practice, which may itself evolve through the consensus of a growing community of practice. Aside from enabling place owners to understand and effectively respond to local air quality issues, scaled uptake of OPENAIR best practice can form the foundation of higher utility state and national-scale data sharing. It can do this, following Gamble and Goble (2011), by helping to standardise data collection and labelling and establishing trust and shared language between data producers and data users.

The OPENAIR pilot data feed has continued to operate after the project ended. Its modular design has the potential to be developed and scaled to support more device types, more varieties of air quality data, a greater range of contextual metadata, more overall data inputs, and improved data processing. This positions the pilot data feed as a working publicly owned minimum viable product

(MVP) version of a prospective future state or national-scale data infrastructure for the widespread exchange and harmonisation of near-real-time air quality data from low-cost sensing networks.

Scaling of this type of data infrastructure would have numerous benefits. For state and territory authorities concerned with ambient air quality monitoring and management, scaled data sharing infrastructure based on the OPENAIR pilot data feed can enable the aggregation and harmonisation of low-cost sensor data from diverse locations where no regulatory data is available. Combined with improved best practice data collection and labelling for low-cost sensing, this can support 'supplemental network monitoring', where spatial gaps in a regulatory network are filled by data from many lower-cost devices (Williams et al., 2014). Widespread access to increasingly standardised near-real-time low-cost sensor data of appropriate quality may help to improve the accuracy and overall capabilities of now-casting, forecasting and real-time pollution dispersion models. This has potential application in areas of concern such as smoke from bushfires and hazard reduction burning, as it can inform improved fire and smoke management, and improved communications between public authorities and with the wider public.

Local governments and other users of low-cost sensing technology can benefit from sharing their data with a centralised service that provides validation, correction, augmentation, and forecasting; capabilities typically out of reach for most local authorities. Centralised data processing can also improve trust and provide assurance that advances public data applications. Furthermore, sharing and harmonising data across jurisdictions addresses the transboundary nature of air quality issues, enhancing regional modelling capabilities and facilitating collaborative multi-stakeholder responses. OPENAIR may be seen as a significant practical step forward in enhancing air quality management and public health outcomes at local and regional scales.

A final consideration is the potential for OPENAIR to create impact beyond the air quality domain, as a notable contribution to the emerging human centred smart city paradigm. Best practice resources such as the Impact Planning Cycle can be understood as frameworks for the strategic design and delivery of *any* smart sensing project, making OPENAIR relevant to practitioners across the whole smart city sector. The project methodology, which combined a coalition of academic expertise with local government participants and state government leadership, is also noteworthy because it demonstrates a potentially repeatable approach for supporting sectoral uplift of other emerging smart technologies. Thus, the success of the OPENAIR approach could position it as a blueprint for future state-funded projects. Finally, a scaled data-sharing infrastructure based on the OPENAIR pilot data feed may be expanded to accommodate other types of environmental (e.g. meteorological, noise, water quality, soil moisture) and non-environmental (e.g. people counts, traffic counts, GPS coordinates) low-cost sensor data. This could facilitate diverse new data-driven solutions to urban challenges and may support significant progress towards healthier, more sustainable, resilient and equitable cities, assisting Australia in pursuit of its Sustainable Development Goals and Net-Zero targets.

7. Conclusion

This paper has positioned OPENAIR as significant contribution to the emerging field of smart low-cost air quality monitoring. A high-level overview of project methodology, best practice resources, community of practice and pilot data feed has been provided, with discussion grounding these activities in smart city and environmental data discourse. The author notes the potential for future papers and further research relating to OPENAIR. This includes investigation of the six participant Council projects following the end of the formal OPENAIR project, including assessment of actual adoption of best practice methodology and operations, and estimation of impact creation. Regarding the pilot data feed, this paper has not included technical information about the data schema, APIs or detailed architecture, which may be expanded on in future papers, alongside updates on any future development of the data feed.

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