Using Knowledge Graphs for Architecting and Implementing Air Quality Data Exchange: Australian Context

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ABSTRACT

The air quality data ecosystem consists of several interacting actors such as government agencies and researchers that collect large volumes of data from different air quality monitoring stations via IoT sensors and data systems. The challenge is: how to enable data linking and sharing in the complex and federated data ecosystem for more comprehensive research and reporting for air quality improvement? This paper presents a knowledge graph-based approach for architecting and implementing the air quality data exchange platform for enabling the data linking and sharing in the federated air quality data ecosystem. The application of the proposed approach is demonstrated with the help of an air quality data case study example in the Australian context. This work has been done as a part of the large air quality digital data infrastructure project with the state and local government. The learnings from this paper can be used by government agencies and researchers for architecting and implementing knowledge-graph based data exchanges as appropriate to their context.

CCS CONCEPTS

• **Enterprise information systems**; • **Information integration**; • **Data exchange**; • **Data warehouse**; • **Federated databases.**;

KEYWORDS

Air Quality, Data Architecture, Data Ecosystem, Knowledge Graph

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1 INTRODUCTION

There is a significant interest in ecosystem-oriented architecture approached to modelling complex and federated enterprises and government ecosystems [23]. Data ecosystem, as a part of the overall ecosystem, involves several interacting actors and data systems that collect and use data and information for mutual benefits [1-3, 24-25]. There are several types of data ecosystems such as health data ecosystem, finance data ecosystem and similarly air quality data ecosystem, which is the focus of this paper. Here the question is: why do we need to be concerned about the air quality data ecosystem? This is because that with the increasing urbanization and related respiratory diseases, air pollution and air quality are a significant concern for general population, as well as healthcare providers, government policy makers and urban designers [16]. Air pollution occurs by the release of harmful particles or gases into the environment, through industrial settings, transport systems and natural disasters such as fire and toxic water floods [17]. Air quality can be defined as the degree to which the air is suitable or clean enough for humans and the environment [18].

There are number of measurements defined to quantify air quality based on the number of airborne concentrations of major pollutants such as atmospheric particulate matter (PM 2.5/10), carbon oxides COX (CO-CO2), and sulphur oxides (Socks) [4, 18]. Australia is a diverse country, where air quality data is collected and managed by several individual government agencies, particularly at state and local council levels, and researchers from different air quality stations via heterogenous IoT based platforms for the analysis and reporting [16] within the overall Australian air quality data ecosystem. These platforms could be generic such as AWS, Google, MS Azure, and IBM IoT based platforms or bespoke air quality specific such as Clarity, Environut, Purple Air and ThingsBoard platforms [16]. IoT sensors are physical devices deployed in the field to collect air quality data, which is then sent over the Internet or other relevant networks to IoT platforms for further processing and storage [6].

These IoT platforms have their own individual architecture and implementations for sourcing and managing the air quality data [7-8]. For instance, individual agencies and researchers source data in real-time via the air quality monitoring IoT devices [9], and then store and use it for analysis and reporting for evidence-based decision and policy making for air quality [10]. While air quality data can be collected by individual agencies and researchers, however, there is an opportunity to link and share this data via metadata rather than making redundant individual copies of the same dataset again and again by the actors operating in the data ecosystems. Data can be collected once and shared multiple times to avoid data quality issues (e.g. duplication, consistency, accuracy, validity, timeliness), synchronisation risks and reduce cost. Thus, there is a significant interest to link and share air quality data via metadata for a comprehensive view of the connected data for reporting and air quality improvement policy making. This draws our attention to the following challenge:

Research Question: how to enable data linking and sharing in the complex and federated data ecosystem for more comprehensive research and reporting for air quality improvement?

This paper proposes a knowledge graph-based approach for architecting and implementing the air quality data exchange platform

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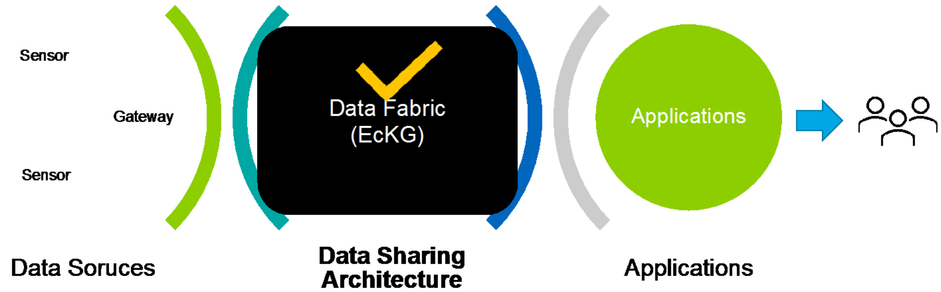

Figure 1: Knowledge graph-based data exchange for data sharing

for enabling the data linking and sharing in the federated air quality data ecosystem [26-27]. The application of the proposed approach is demonstrated with the help of an air quality data case study example in the Australian context. Figure 1 illustrates a simplified and high-level version of proposed knowledge graph-based data exchange architecture for the air quality data ecosystem. The data fabric here is identified as the Enterprise Ecosystem Knowledge Graph (EcKG), which is the focus, scope, and the main contribution of this paper. We propose to use EcKG within a knowledge graph-based data exchange or data fabric to link and share air quality data using metadata from different data sources (e.g. IoT sensors and gateways) depicted in the left-hand side of Figure 1 with the end users of air quality applications (e.g. reporting, visualization, dashboard, insights) depicted in the right-hand side of Figure 1. This can provide comprehensive research and reporting capabilities without the need of duplicating data or inefficient data sharing approaches that can lead to data duplication, limited traceability, and lineage as well as data privacy violations.

It is important to note here that this work has been done as a part of the OpenAir project, a large-scale air quality digital data infrastructure project with the New South Wales (NSW) state and local government agencies (i.e. councils) in Australia [28]. Detailed discussion about the whole architecture and its application are beyond the scope of this paper. More details about the overarching project can be found online [28]. Here, we are detailing and extending the data sharing aspect of the air quality project by using a knowledge graph.

The paper is organized as follows. Firstly, it provides research background and motivation. Secondly, it discusses the research method. Thirdly, it presents the proposed knowledge graph-based data exchange architecture. Fourthly, it discusses the implementation via a prototype demonstration using Australian public air quality data case study before concluding.

2 RESEARCH BACKGROUND AND MOTIVATION

2.1 Air Quality Data Ecosystem

Data ecosystem is a network of actors, both human and technology, that source and process data for mutual benefits using different data systems [2-27]. It can be defined as a system of data systems that "combines data from numerous providers and builds value through the usage of processed data" [21]. There are several different types of data ecosystems such as business data ecosystem and government data ecosystem. Government data ecosystem is a super data ecosystem, which consists of several government sector or data domain specific data ecosystems. For instance, it can be further classified into government health data ecosystem, financial data ecosystem and similarly air quality data ecosystem, which is the scope of this paper. These data ecosystems operate in the federated information sphere or "infosphere" [2]. Actors in the air quality data ecosystem source data from IoT sensor devices, store and process it using their data systems (e.g. databases, data lakes, data warehouses) for reporting, evidence-based decision making and actions [16, 22]. IoT devices provide the technical capability to continuously source air quality data; however, they have limited computational and data storage capacity. Therefore, IoT devices send the sensed air quality data to data systems that store and manage air quality data in-house or in the cloud [16-18]. Cloud based data systems enable the on-demand, secure and scalable air quality data storage, network, and computing capabilities for air quality data management and processing [10].

2.2 Air Quality Data Linking and Sharing

Traditional approaches of point-to-point and ad-hoc integration of data systems hinder the ability of air quality data linking and sharing between different actors operating in the federated data ecosystem. Furthermore, sourcing, integrating, and sharing air quality data to/from different actors, in different formats, via multiple channels and across jurisdictions in a data ecosystem is not only difficult; rather, sometimes, it is not feasible. Also, there is an opportunity to collect air quality data once, link it and share it with others without duplicating it at many places, which can be a risk to data privacy and expensive to manage. Thus, this need draws our attention to the following challenge:

Research Question: how to enable data linking and sharing in the complex and federated data ecosystem for more comprehensive research and reporting for air quality improvement?

This paper proposes that the above-mentioned need of air quality data linking and sharing, in the data ecosystem, can be addressed via a data exchange [2] underpinning knowledge graph-based semantic layer. Our intent is not to create another centralised data hub or data marketplace or data warehouse which can be a honey pot for hackers. However, an existing centralised data hub or data marketplace can be connected to the proposed data exchange either as an air quality data source or destination via the data exchange. Thus, a user may source and share air quality data to/from a data hub or data marketplace by using the data exchange. This research proposes the development and implementation of air quality data exchange architecture using the. digital ecosystem information exchange reference architecture [2].

2.3 Context of Study

Our study is conducted and evaluated in the Australian government context for air quality monitoring and sharing. Therefor it is important to mention that this work is aligned with the Australian Government Architecture (AGA) [1], as defined by the Digital Transformation Agency. AGA provides resources to guide the design of new digital platforms and assess existing platform capabilities. Particularly, for our data exchange work, we have considered four capabilities defined under 'Shared Data and Insights' Domain, which include Business Intelligence Analysis, Data Management, Metadata and Semantics and Operational Analysis. Further, it is important to note here that NSW State government also has data sharing principles, which are developed to guide and encourage data sharing by NSW government agencies, by holding data in controlled manner and sharing them with stakeholders in the data ecosystem to deliver good outcomes for residents. These principles and supporting recourses provide guidance related to publish open data, create data sharing agreements as well as to measure the data maturity. In nutshell, the proposed air quality data exchange architecture work is aligned to both the Australian federal and state government principles, enhancing its value/enabling it to be used by the people, business, and government. Since data exchange is a complex architecture, this paper mainly focuses on the metadata and sematic data fabric component of the data exchange architecture, which is implemented using the enterprise knowledge graph-based approach and platform for data linking and sharing.

2.4 Enterprise Knowledge Graphs for Data Linking and Sharing

The term 'Knowledge Graph' was coined by Google, and it refers to a general concept of capturing and representing entities and their associations or relationships for specific domain, which is called domain ontology as well [12]. An entity is represented as a node (e.g. Person, Air Quality, Location) and a relationship between entities is represented as an edge (e.g. "Air Quality" of "Location") in a knowledge graph [26]. A knowledge graph is made of several linked nodes. Thus, knowledge graph is very useful for linking connection-oriented data, and suits well of our need for representing and linking air quality data.

Ontologies and semantic web technologies are the foundation layer of knowledge graphs that provide formal descriptions and shared terminology as well as a basis for formal representation and reasoning on the domain knowledge. The systematic literature review by Bandara et al. [13] provides an overview of how ontologies and semantic web technologies are utilized in knowledge graph-based data representation, analytics, and management. There is a general understanding that knowledge graphs can be used to design the data exchange architecture [14], which warrant further research. Existing literature explore the idea of using knowledge graphs in digital ecosystems for knowledge sharing [15] and transparency, particularly for healthcare [5] and energy data eco-systems [11]. There is a need for further work to understand how knowledge graphs can be used for data linking and sharing in data ecosystems such as air quality, particularly considering the complexities associated with IoT infrastructure, real-time data management, associated policies, and regulations, including wide variety of stakeholders who may want to consume the data for different purposes. As indicated earlier [12], knowledge graph-based approach seems useful to link large amount of data using metadata that come from diverse sources and various domains and cater for diverse information needs of the end-users. Thus, this paper proposes a knowledge graph-based approach for architecting air quality data exchange that can handle the complexity of multi-stakeholder data sharing such as at the scale of NSW state and local government.

3 RESEARCH METHOD

This research has been conducted as a part of a large-scale air quality digital data infrastructure project (OpenAir project [28]) in Australia. This research applied the well-known design science research (DSR) method to develop and evaluate the proposed knowledge graph-based air quality data exchange architecture artifacts [20]. DSR method has been chosen as a preferred approach due to the practical and applied nature of this research project. DSR method has been organised into four major stages: (1) research background and problem formulation, (2) design, (3) evaluation and (4) conclusion.

Research background and motivation (as noted earlier) involved the review of existing work, which resulted in the identification of research problem including the proposed solution. Design stage focused on developing the data exchange architecture artifacts using the knowledge graph. This stage used the IoT Alliance Australia Reference Architecture (IoTRA) framework [19] and Digital Ecosystem Information Exchange Reference Architecture (IERA) [2] as kernel theories or theoretical lenses to systematically develop the proposed air quality data exchange architecture to address the practical research question in hand. The IoTRA has been used because it provided the overall layers to design the IoT enabled air quality data ecosystem, whereas the IERA has been used to specially inform the air quality data exchange architecture design within the overall data ecosystem, which is the scope of this paper. Evaluation stage focused of assessing the proposed design artifacts using the evaluation method (e.g. expert evaluation, proof of concept) and related criteria (e.g. applicability, comprehensiveness). Here, the proposed air quality data exchange architecture design was implemented (as a proof-of-concept) using the Stardog technology platform for enterprise knowledge graph for the Australian air quality data case study. The purpose of the proof-of-concept implementation was to evaluate the applicability of the proposed knowledge graph-based data exchange architecture. This ensured that the proposed air quality data exchange architecture is fit for the purpose. It is anticipated that learnings from this initial architecture design and

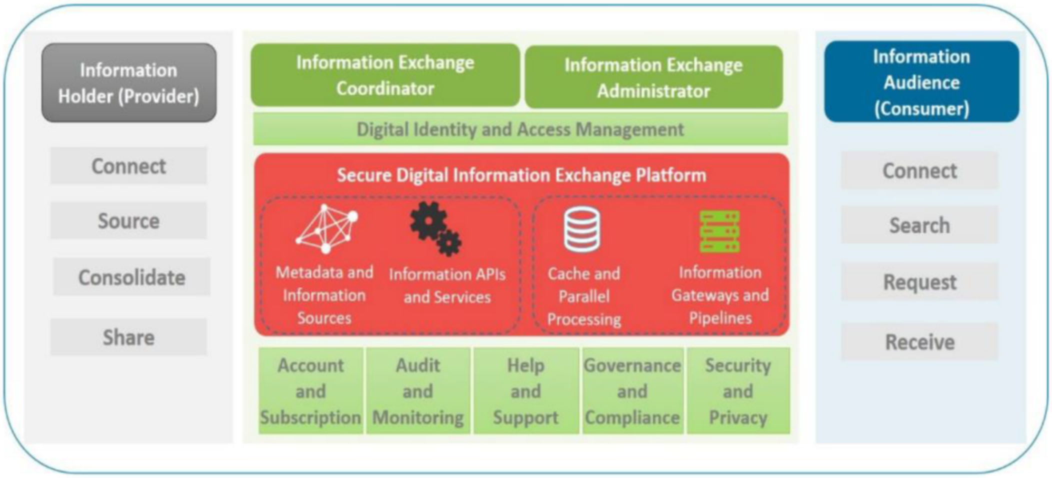

Figure 2: Digital information exchange reference architecture (IERA)

proof of concept evaluation can further help to scale and tailor the proposed architecture for other similar contexts.

4 THE AIR QUALITY DATA EXCHANGE

Air quality data exchange architecture design has been guided by the IoTRA [19] and IERA [2], as mentioned earlier. The IoTRA is used to specify the overall architecture stack layers: IoT endpoint, edge gateway, connection management, intelligence enablement, application enablement and user interface. The data exchange resides in the intelligence enablement layer of the IoTRA stack. The IERA specifies three major components for the data exchange: actors, services, and platform (Figure 2) (based on [2]). There are four key types of actors. Information Holder (Provider), and Information Audience (Consumer) provide and consume data and information via the information exchange platform (the middle layer), which is coordinated and administrated by other two types of actors (i.e. information exchange coordinator and administrator). Provider may use the connect, source, consolidate and share services of the exchange platform for air quality data sharing. Consumer can access air quality data by using the connect, search, request and receive services. The air quality data sharing is overseen and facilitated by the exchange coordinator via governance and compliance services, whereas exchange administrator handles the exchange operations, which includes exchange identity and access management, user account and subscription (e.g. air quality data sharing agreements), audit and monitoring, help and support, and security and privacy.

The core to the air quality data exchange is the metadata and information/data sources, which are used to link the data from different sources and then shared via data APIs and services. Metadata may include data definitions, schema, structure, scripts, logs, source, and destination locations. It is not feasible to discuss the detailed implementation of the whole data exchange in a single paper. Thus, this paper mainly discusses the "metadata and information sources" component of the exchange using the enterprise knowledge graph (illustrated at the third layer from the top, in the middle of Figure 2), which is core to air quality data linking and sharing problem.

We propose to use a knowledge graph to represent and manage metadata and data sources. As defined earlier, a knowledge graph captures domain knowledge as entities (nodes) and relationships (edges), in a graph structure. Our proposed knowledge graph can be illustrated as four layers in model-driven design (see Figure 3), where M3 [29], Meta Metamodel is the semantic web standards, which we used to implement proposed air-quality data exchange meta-model (M2). The data applied within that metamodel are at level M1, capturing the actual air-quality data and eco-system (M0).

The proposed knowledge graph (M2) can be used to capture metadata and minimal actual air quality data necessary for users to find and access data stored in individual data sources (e.g. air quality monitoring stations) as demonstrated in figure 4 below. Air quality data owners can control quality, versioning, and access via the data exchange. Users can search and integrate or link air quality datasets that best fit their needs. Actual data streaming from each data source, usually captured by multiple air quality monitoring sensors, is heterogenous and voluminous. It is not necessary to store those streaming data points on a knowledge graph. The knowledge graph management platforms such as Stardog [30] can support with techniques to unify such data through virtual graphs and let the system designers declaratively map and link air quality data into the knowledge graph metadata and query it when needed.

5 APPLICATION CASE STUDY

To demonstrate our proposed approach of utilising knowledge graphs for air quality data linking and sharing, we have developed a proof-of-concept knowledge graph prototype, based on public domain datasets that record and publish air quality data and related metadata in the state of New South Wales, Australia.

5.1 Application Overview

For this application, we have selected a case study of air quality monitoring digital platforms operating in state of New South Wales

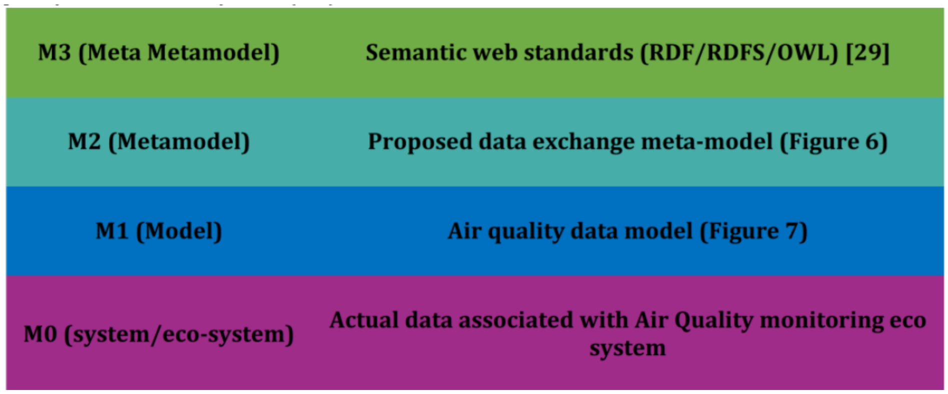

Figure 3: Modelling layers of proposed knowledge graph

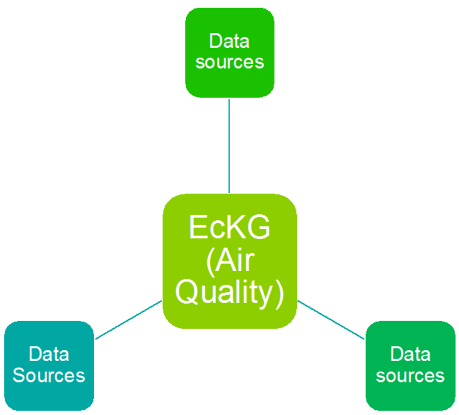

Figure 4: Ecosystem knowledge graph (EcKG): data sources and metadata

(NSW), Australia. Data for this case study was obtained from air quality data and metadata published for public access through SEED initiative [31]. It is designed by NSW Government for exchanging environmental data between different government agencies and researchers. An external user can download a local copy of the metadata and associated datasets from SEED. They can search and review the metadata to identify datasets that best match their needs. Integration of datasets can be done manually. Air quality data in SEED platform are coming from NSW Air Quality Monitoring Network (AQMN), a network of air quality monitoring stations situated at different locations in NSW, under different municipal regions. Each station is unique in terms of technology used as well as what air quality monitoring metrices they measure.

Knowledge graph-based data exchange can be used here for data linking and sharing without necessarily storing the actual air quality data. As noted earlier (section 3), this project used the IoTRA stack the overall air quality data ecosystem. where the proposed data exchange is located in the intelligence enablement layer. Figure 5 provides an overview of air quality data ecosystem layers (levels 1-7) with sensors and IoT communication devices in the bottom and applications and user interfaces residing at the top. Layer 3 is illustrated by arrows connecting layer 2 and 4, as it tightly couples with layer 2 and 4 and focuses on the actual network and connectivity. At level 4, the data collection and communication will be done at air quality monitoring station level. Then the IoT hubs will transfer the data to storage platforms (at level 5), that can be organised at regional or state level. Initial data processing would occur here to clean and transform the data for data linking and sharing.

We place our proposed air quality "Data Sharing KG" for the data exchange in layer 5 of the digital data ecosystem illustrated in Figure 5, as our objective is to capture all the metadata about air quality data and data sources including their access protocols. Each geographical region (e.g. state and local government areas) can have their own individual knowledge graph, which can also be linked to a central knowledge graph at the national level such as national air quality data exchange. Actors within and across the regions can directly link and share their metadata and data sources using the knowledge graph (nodes and edges) without dealing with the complexity of underlying technology stack layers. End users can search, understand, identify air quality data and their sources using metadata stored in the knowledge graph and then they can query actual air quality data via applications in the application enablement layer (level 6) and their respective user interfaces (layer level 7).

5.2 Prototype

We developed a prototype of "Data Sharing KG" in layer 5 of air quality data ecosystem, obtaining metadata from NSW Air Quality Monitoring Network through SEED platform. This metadata was used to design and implement a knowledge graph to showcase our proposed approach using the knowledge graph Stardog platform. For demonstration purpose, our knowledge graph has three key entities: Monitoring Station, Region, and AQ-Metric, and their relationships. Each entity has a set of attributes to capture the additional information. For example, each monitoring station entity records its 'ActiveStatus:Boolean', 'Address:String', 'Datasource:URL', and 'ComissionedYear'. 'ActiveStatus:Boolean' attribute can be used to identify monitoring stations that are no longer active, or 'Datasource:URL' can be used to identify how to

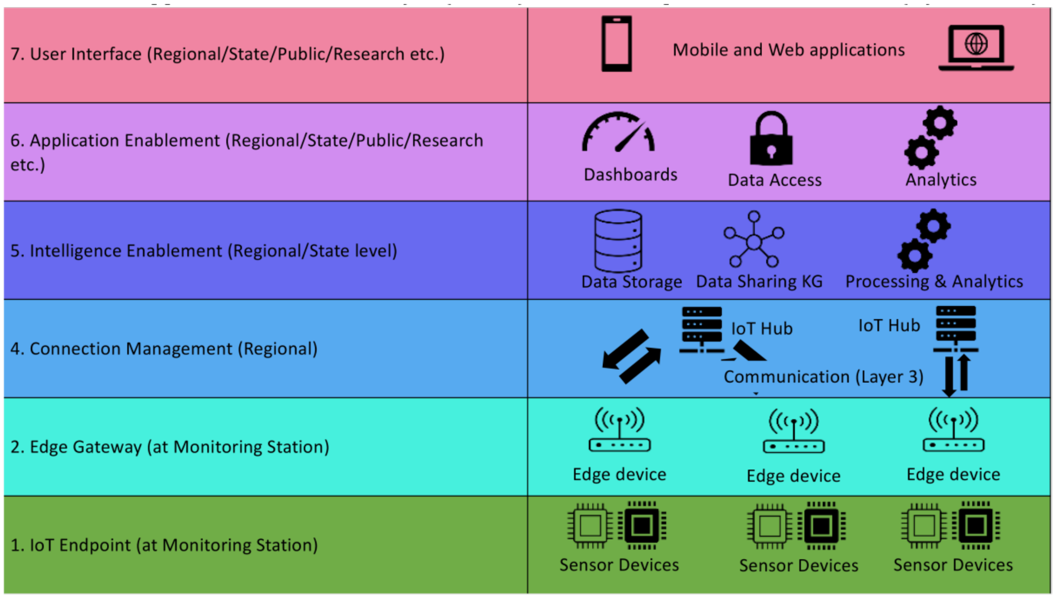

Figure 5: Air quality data ecosystem

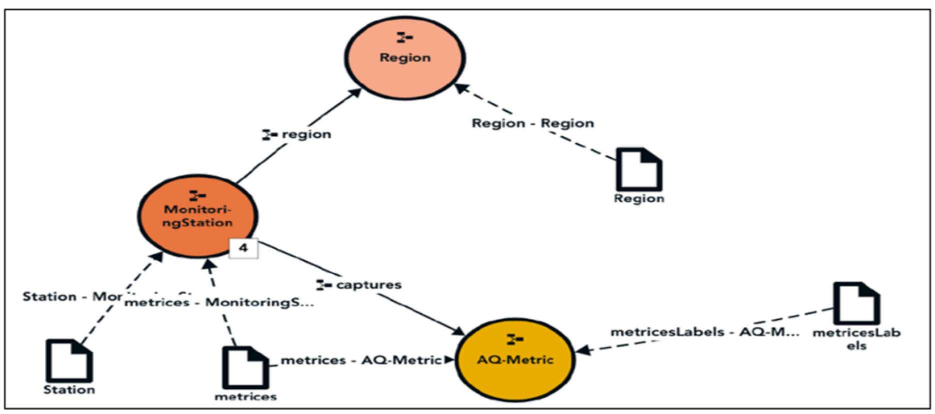

Figure 6: Data exchange knowledge graph meta-model for air quality data

access raw air quality data associated with each station. Figure 6 illustrates how different metadata sets are linked to these entities in the knowledge graph without copying the actual data from the source (data stays at their sources). Once we have the metadata mapped into the knowledge graph, we can inspect individual entities and linked data using queries. For example, Figure 7 shows us data on one monitoring station, labelled 'Aberdeen', located in 'Upper Hunter' region (NSW), that capture three air quality metrics. Queries, written in SPARQL query language, can be used to explore the knowledge graph as shown in Figure 8. This simple example query retrieves a list of air quality monitoring stations that capture the air quality metric 'PRECIPITATION'. These queries can be built into applications so that users can easily search and share metadata and linked data. Another advantage of using a knowledge graph is that the schema can be queried and published as well. Thus, it is easy to integrate other knowledge graphs and metadata to air quality knowledge graph (e.g. demographic data or health data) to obtain detailed semantics of the data. This initial prototype of knowledge graph indicated its usability for architecting the data exchange for data linking and sharing using the metadata without the need for duplicating and transferring the data as we do in traditional centralise data warehouses or data lakes.

6 CONCLUSION

Data linking and sharing across the federated data ecosystem is an arduous undertaking. This paper discusses the important concepts of complex and federated data ecosystem and its data exchange architecture and implementation for air quality data linking and sharing in the Australian context. More specially, it proposes the use of enterprise knowledge graph-based data exchange to link and share the air quality data for comprehensive reporting and coordinated actions without the need for duplicating the data collections

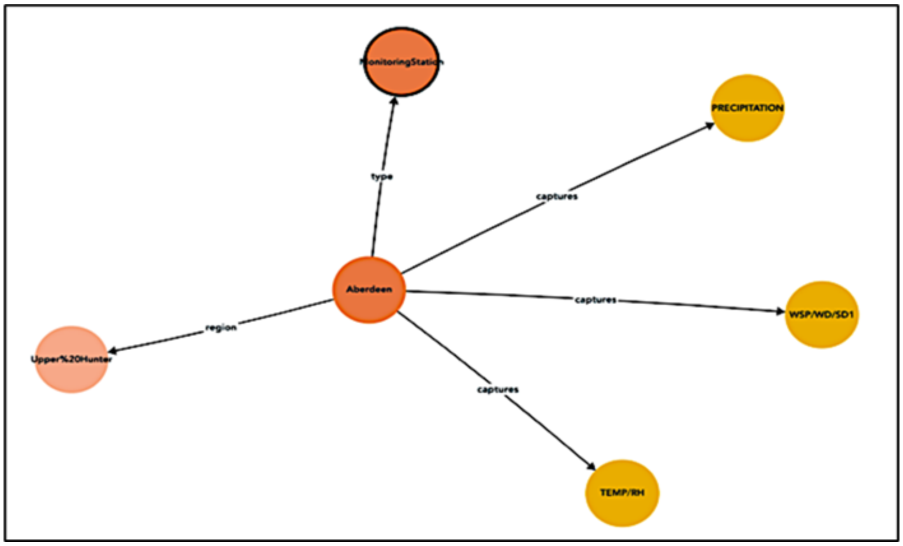

Figure 7: Data exchange knowledge graph model for 'Aberdeen' monitoring station

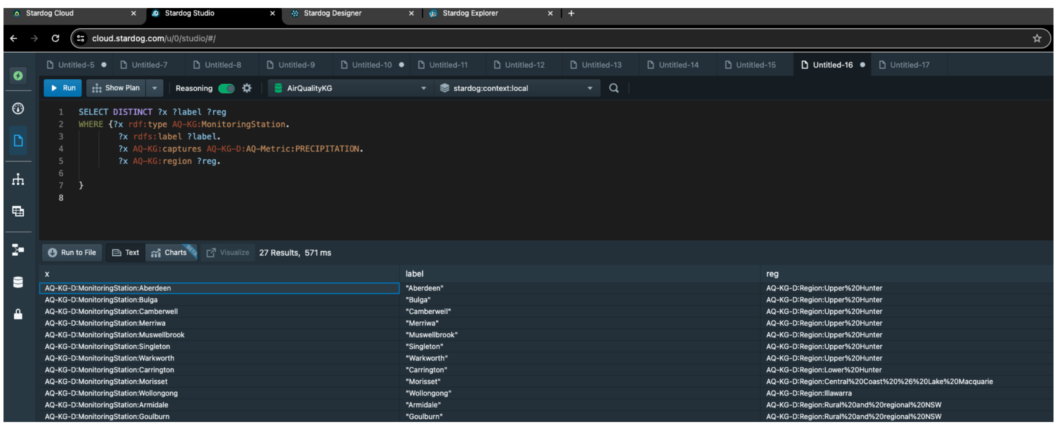

Figure 8: SPARQL query run on the Knowledge Graph through Stardog platform

and its storage several times by the individual actors operating in the data ecosystem. Metadata about the data and its sources can be mapped in the enterprise knowledge graph of the data exchange, which then can be searched and requested by the end users. The key insight is that data exchange can support the principle of collecting data once, then linking and sharing it multiple times via the enterprise knowledge graph. Key benefits of this approach are the improved information security and reduced cost of maintaining data storage and access. It is anticipated that learnings from this research can be used to inform future research in the practical and applied area of research in knowledge graph-based data exchanges.

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