LUT University
School of Engineering Science
Erasmus Mundus Master's Program in Pervasive Computing & Communications for Sustainable Development (PERCCOM)

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CAVISAP: CONTEXT-AWARE VISUALIZATION OF AIR POLLUTION WITH IOT PLATFORMS

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ABSTRACT

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CAVISAP: Context-aware visualization of air pollution with IoT platforms

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Air pollution is a severe issue in many big cities due to population growth and the rapid development of the economy and industry. This leads to the proliferating need to monitor urban air quality to avoid personal exposure and to make savvy decisions on managing the environment. In the last decades, the Internet of Things (IoT) is increasingly being applied to environmental challenges, including air quality monitoring and visualization. In this thesis, we present CAVisAP, a context-aware system for outdoor air pollution visualization with IoT platforms. The system aims to provide context-aware visualization of three air pollutants such as nitrogen dioxide (NO_2), ozone (O_3) and particulate matter ($PM_{2.5}$) in Melbourne, Australia and Skellefteå, Sweden. In addition to the primary context as location and time, CAVisAP takes into account users' pollutant sensitivity levels and colour vision impairments to provide personalized pollution maps and pollution-based route planning. Experiments are conducted to validate the system and results are discussed.

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Melbourne, 11 April 2019

Meruyert Nurgazy

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LIST OF SYMBOLS AND ABBREVIATIONS

AMQP	Advanced Message Queuing Protocol
AQI	Air Quality Index
AWS	Amazon Web Services
CoAP	Constrained Application Protocol
CST	Context Spaces Theory
DDS	Data Distribution Service
ECSTRA	Enhanced Context Spaces Theory Based Reasoning Architecture
EEA	European Environmental Protection Agency
GIS	Geographical Information Systems
GPLv3	GNU General Public License, version 3
HTTP	Hypertext Transfer Protocol
HTTPS	Hypertext Transfer Protocol Secure
IERC	Internet of Things European Research Cluster
IoT	Internet of Things
LGPLv3	GNU Lesser General Public License, version 3
MQTT	Message Queue Telemetry Transport
M2M	Machine to Machine
NFC	Near-field Communication
REST	Representational State Transfer
UN	United Nations
XMPP	Extensible Messaging and Presence Protocol
CO	Carbon Monoxide
CO_2	Carbon Dioxide
NO_2	Nitrogen Dioxide
O_3	Ozone
PM	Particulate Matter
SO_2	Sulphur Dioxide

1 INTRODUCTION

Air pollution is a rapidly evolving concern in the past decades with the growth of pollution sources worldwide. According to the European Environment Agency (EEA) pollutants are released to the air from a wide range of sources including transport, agriculture, industry, waste management and households [1]. Rapid urbanization and industrial growth exacerbate the problem and the pressure felt severely in big cities. However, air pollution does not respect borders. Air pollutants and heavy metals are carried by wind, contaminating water and soil far from the origin [2]. Therefore, air pollution is not a problem of solely industrial regions but a global burden which affects all parts of society. According to the World Health Organization (WHO), 92% of population in our planet lives in the areas that exceed ambient air quality limits. In addition, the report states that air pollution is the largest environmental risk to health, being responsible to each ninth deaths per year. Moreover, statistics show that outdoor air pollution alone is a cause of 3 million deaths annually [3].

Human exposure to air pollution may cause different health issues depending on the duration of exposure, type of pollutant and the toxicity level of the pollutant. The WHO present air quality guidelines to explain in details health effects of various pollutants [4]. The health effects of air pollution can vary from difficulty in breathing, nausea or skin irritation to cancer. The most widespread health effects observed by different investigations include reduced lung functioning, asthma attacks, development of respiratory diseases and premature death [5].

Atmospheric environmental protection, including air quality management, response policies, health impact and risk assessment as well as air pollution modelling would be impossible without quantitative description of air quality with measurable quantities. The aim of the air quality management is to keep the ambient air clean enough so that it is safe for the public health and the environment. In order to assess status of the air, current air quality must be monitored. Public awareness of air pollution can contribute to both reducing emission levels and decreasing exposure. Moreover, the air quality information is required by scientists, regional and national policy-makers and planners to enable them to make savvy decisions on managing the environment. Air quality monitoring provides necessary scientific basis for developing policies, setting objectives and planning enforcement actions [5]. Despite the importance of measurements, in many cases, monitoring alone may be insufficient for the purpose of fully defining population exposure in the environment. Therefore, monitoring often needs to be combined with other objective assessment techniques, including modelling, personalization and visualization of measurements. Traditionally air quality monitoring is based on air quality stations operated by national environmental protection agencies. These stations provide highly accurate measurements; however, the coverage area is limited. Therefore, numerous new approaches are emerging in order to provide highly resolved air quality visualization [6].

In the last decades Internet of Things (IoT) is increasingly being applied to environmental challenges, including air quality monitoring, visualization and prediction. [7] defines IoT as "an interconnection of sensing and actuating devices providing the ability to share information across platforms through a unified framework." Introducing IoT into the field of environmental monitoring provides opportunity to get more accurate data in near real-time [6]. However, there are numerous challenges in adopting IoT for environmental issues. According to CISCO's report, in 2017 there were 18 billion Internet-connected smart devices, their forecasted number by 2022 is 28.5 billion [8]. This leads to the generation of an enormous amount of data that has to be stored, computed and visualized in an easily interpretable and efficient form.

Data generated by billions of devices might not have any value unless it is processed and interpreted. Numerous data collection, modelling and reasoning techniques are evolved to add a value to raw data coming from IoT devices [9]. One of the fields which gained increased significance on processing raw data is *context-aware computing*. Context-aware approach deals with raw information to provide meaningful context information which can characterize the user's situation and provide personalized services. Location, time, user and activity can be considered as primary context types. Systems which use context in order to provide service are considered as context-aware [10].

Application of the context-aware approach to outdoor air pollution monitoring enable systems to understand user's needs and provide relevant information. Consequently, context-aware computing enables to process data efficiently and store only meaningful information which is crucial in the era of billions of smart connected devices and big data.

1.1 Research Motivation

In September 2015, countries around the world adopted global Sustainable Development Goals (SDGs) defined by United Nations (UN). The set of goals are aimed to end poverty and hunger, protect the planet and resources and increase the quality of life and others as presented in Figure 1. Sustainable Development Goal 3, target 3.9 focuses on ensuring well-being and good health for world population considering substantially reducing the number of illnesses and deaths caused by air pollution by 2030 [11].

Figure 1. UN Sustainability Development Goals. [12]

The 2009/10 Global Information Technology Report from World Economic Forum's (WEF) stated that "information and communication technologies meant to play important role to enable sustainable growth". The 2019 WEF IoT for Sustainable Development project analysis found that 84% of IoT deployments are currently addressing, or have the potential to address, the SDGs as defined by the UN [13].

The main motivation of this thesis is to apply IoT to create public awareness on outdoor air pollution. Creating knowledge and awareness of air quality status which citizens can view and personalize is critically important, because it affects health and well-being [14]. The study aims to use context-aware approach to provide personalized and task-relevant information on air quality which enables citizens and policy-makers to take immediate actions and avoid polluted sites.

Motivating scenario. Consider the following example illustrating the necessity for real-time visualization of outdoor air pollution according to user context. Alice and Jack live in the same neighbourhood in Skellefteå. They both work downtown and commute to there by bike. Figure 2 illustrates possible routes from their neighbourhood to the work.

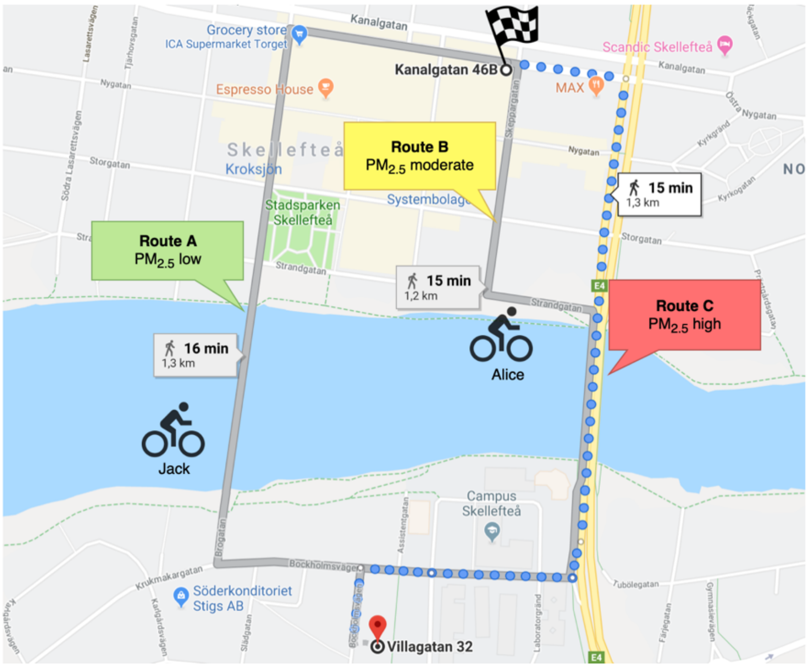


Figure 2. CAVisAP motivating scenario illustration.

Jack has extremely high sensitivity to small particles; therefore, he always needs to be cautious about air pollution. However, Alice is a healthy person. The same level of pollution exposure can affect them differently.

The illustration shows three routes A, B and C with low, moderate and high levels of particulate matter pollution respectively. For Jack even moderate level of particulate matter is critical and his overall AQ situation is poor at route B and C. Therefore, Jack needs to take route A. Even though high level of particulate matter is critical for Alice, she is tolerant for the moderate level. Therefore, Alice can take route B which is shorter but more polluted than route A. Conventional navigation systems such as Google Maps [15] do not consider user's context when providing route alternatives. Therefore, there is a need to build a context-aware system which enable walkers and bikers to avoid polluted areas.

1.2 Problem Definition

The core problem of this work is to incorporate context-awareness to IoT data visualization in outdoor air pollution use case. The same levels of air pollution data streams received from IoT devices might have different meaning for users with different pollution sensitivity levels. Therefore, data visualization must be personalized according to the user context.

1.2.1 Research Aim, Questions and Objectives

The **research aim** of this thesis is *to model, build and validate a real-time IoT-enabled context-aware visualization system applied for outdoor air pollution use case.*
To address this aim, we define the following **research questions**:

1. *What is the state-of-the-art in the literature applied for IoT-based context-aware air pollution visualisation?*
2. *How to build a context-aware model to personalize air pollution visualisation?*
3. *How to implement and validate the proposed context-aware system for air pollution visualisation?*

In order to answer to each of the research questions the **research objectives** are defined. Each objective tackles a research question in respective order.

1. *To investigate the state-of-the art literature applied for IoT-based context-aware air pollution visualisation.*
2. *To define personalization criteria and develop a generic model for context-aware visualisation of air pollution maps.*
3. *To implement and validate the system prototype in a real-life scenario.*

1.2.2 Research Methodology

It is important to follow a predefined methodology to perform a reliable research. A type of methodology chosen for a research is defined by objectives. This study aims to create an artefact to solve a real-life problem, therefore, Design Science Research Methodology (DSRM) introduced in [16] is chosen as a methodology. The DSRM consists of six steps as shown in Figure 3. The first step is *problem identification and motivation*. A state-of-the-art literature review must be conducted in order identify research gaps. The next step is *defining objectives* of the research. At this stage a novel contribution of the study must be investigated. The next step is *design and development*. A model of the solution must be designed, then implemented. At the *demonstration and evaluation* steps solution of the problem must be experimented and validated. The last step is *communication* where results of the research must be published and shared with the research community.

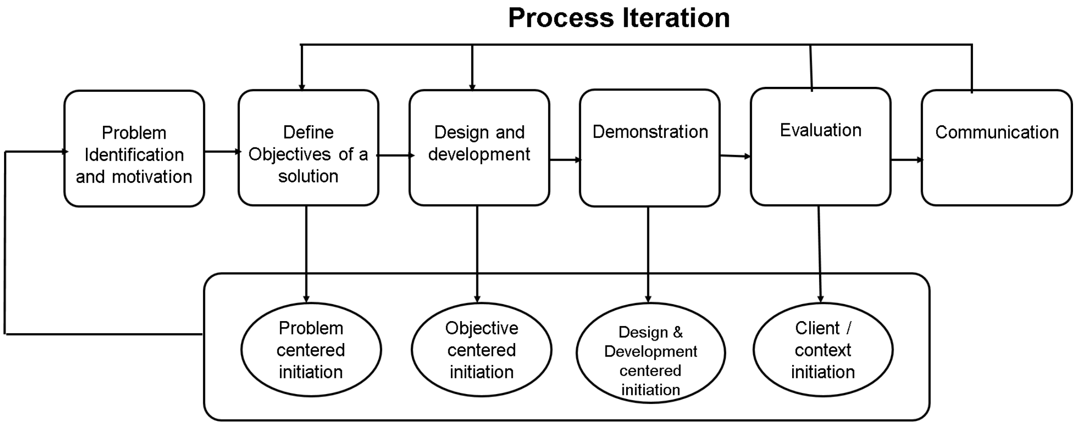


Figure 3. DSRM methodology. [16]

1.3 Research Scope

This thesis is concerned with efficient visualization of air pollution heatmaps for outdoor environments and providing users with pollution-based route planning. The scope of the project covers IoT enabled smart objects with air quality sensing capabilities and open air quality data collection, preliminary processing and aggregation in the IoT platform-based prototype system.

1.4 Contribution

The thesis contribution can be listed as follows

- to propose a model to define user context and provide personalized situation reasoning based on outdoor air pollution;
- to develop a system prototype to illustrate personalized outdoor air pollution visualization and pollution-safe route planning;
- to evaluate the developed system in real-life scenario;

- Moreover, two research papers, containing findings of this thesis were submitted and accepted for publication in the 2019 International Conference on High Performance Computing & Simulation (HPCS 2019) and the 9th International Conference on the Internet of Things [17] [18].

1.5 IT for Sustainability

Numerous definitions for sustainability are given, but the most common one is from United Nations (UN) [19] which states that sustainability is "a development that meets the needs of the present without compromising the ability of future generations to meet their own needs". As a part of PERCCOM program [20], [21] this thesis aims to use ICT capabilities to solve global sustainability issues.

The most popular framework to evaluate sustainability of a system is a triple-bottom-line perspective which considers economic, environmental and social aspects. This thesis considers air pollution use case. Moreover, provision of personalized air pollution heatmaps prevents citizens from inhalation of polluted air. Therefore, the thesis can be considered more as a social project than financial. The three-dimensional sustainability positioning of the CAVisAP system illustrated in Figure 4.

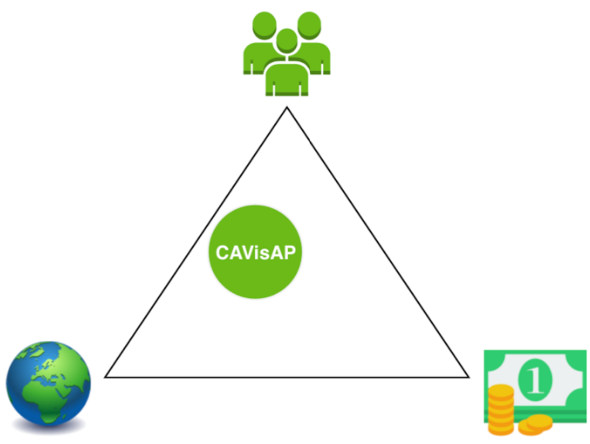


Figure 4. CAVisAP positioning in the sustainability triangle**.**

Creating awareness on air pollution can contribute to both reducing exposure and decreasing emission levels. Moreover, the air quality information is required by scientists, regional and national planners and policy-makers to support them in taking savvy decisions on managing and controlling the environment. Air quality monitoring provides necessary scientific basis for developing policies, setting objectives and planning enforcement actions [5].

The sustainability aspect of the thesis lies on creating awareness on environmental problems by harnessing potential of IoT to sense pollution and providing context-aware visualization which can help citizens to avoid pollution exposure and governments to make informed decisions. At the discussions section a detailed sustainability analysis of the thesis is provided.

1.6 Thesis Outline

The remainder of the thesis is structured as follows.

Chapter 2 – Theoretical Background and Related Work. The second chapter presents state-of-the-art literature review and background knowledge in context-aware air quality monitoring and visualization. Related existing systems were analyzed according to a predefined criterion. The research gaps were identified. The conclusion of this chapter sets up a foundation for the proposed thesis.

Chapter 3 – Context-Aware Air Pollution Visualization Model. In the third chapter we present Context-Spaces Theory (CST)-based context modelling. Algorithms to define user context in terms of pollutant sensitivity, situation reasoning and pollution-safe route building is presented.

Chapter 4 - System Architecture and Implementation. The fourths section demonstrates system architecture, its components and presents system implementation process.

Chapter 6 - Experiments, Results and Discussion. In the sixth chapter the outcome of system testing in real life scenario is presented and model validation is illustrated.

Chapter 7 - Conclusion and Future Research. The last chapter concludes the results of the research and discusses the future work.

2 THEORETICAL BACKGROUND AND RELATED WORK

This chapter introduces the theoretical background work and related literature analysis of the thesis.

2.1 The Internet of Things

A term Internet of Things (IoT) was first introduced by Kevin Ashton in 1999 on supply chain management [22]. According to ITU, IoT is a major enabler of ubiquitous computing which provides a connectivity anytime, anywhere, by anyone and anything [23]. As identified by [24] IoT can be considered as a result of convergence of three paradigms such as Internet-oriented vision(middleware), things-oriented vision(sensors) and semantic-oriented vision(knowledge).

Despite small differences on defining IoT, the vision of IoT has been massively strengthened by statistics and forecasts. Gartner states that there will be 20 billion devices connected to the Internet by 2020 [25]. 98% of survey respondents conducted by McKinsey report that majority of companies in their sector consider IoT initiatives in their roadmap. Moreover, the same source claims that IoT has a potential to generate about $4 billion to $11 trillion in economic value by 2025 [26]. The reason of such huge figures to be forecasted is that connectivity and communication in the IoT paradigm enables its application in many domains. As an example, IoT Analytics group shortlisted the most popular IoT application areas including industry, smart city, energy, agriculture, e-health and supply chain [27].

2.1.1 IoT Architecture

As it was mentioned, the term IoT was coined only two decades ago. Therefore, the paradigm is relatively new to have a single standardized architecture for IoT system. Numerous proposals were made by different research groups. The most simplistic model is three-layered architecture consisting of the Application, Network and Perception layers presented in [28], [29]. Moreover, in [30] authors illustrate extended version of this architecture overall consisting of five layers: Perception, Network, Middleware, Application and Business layers. Since five-layer architecture comprises the one with three layers, we give a brief description of a former one:

1. Perception layer consists of all physical devices such as sensors and actuators and connects physical and virtual worlds.
2. Network layer handles communication between devices and data transmission to the processing layer.
3. Middleware layer or processing layer covers device services management, data storage, filtering and processing.
4. Application layer is responsible for global management of a system based on the object information processed in the lower level. Examples of services in this layer can be smart home or e-health applications.
5. Business layer handles complete management of an IoT system. Business layer builds business models and defines future strategies depending on the data provided by application layer.

These proposals give a basic idea on building blocks of IoT; however, they are limited to describe holistic system architecture of IoT. Therefore, there is a need for a reference model, which could provide a more descriptive overview of the system in a greater level of abstraction. There were several attempts to establish a reference model by numerous research groups. Cisco presented a seven-layer IoT reference model at IoT World Forum in 2014 [31]. The main difference of Cisco's model from the five-layered IoT architecture is introduction of Edge Computing as a layer. Moreover, the model divided middleware layer into two separate layers of Data Accumulation and Data Abstraction, where former is responsible for data storage and latter for data filtering and processing. Figure 5 illustrates three-layered and five-layered IoT architectures as well as Cisco's IoT reference model.

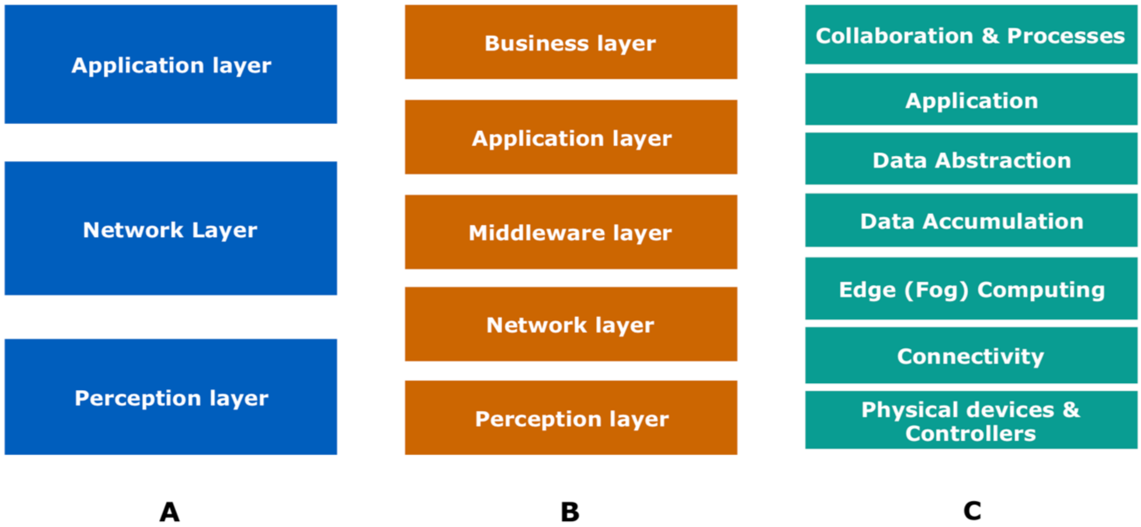


Figure 5. IoT Architecture versions: a) Three-layered; [28] b) Five-layered; [30] c) CISCO reference model. [31]

The same year with Cisco, WSO2 and year later IoT-A demonstrated their versions of reference models for IoT [32], [33]. Overall architecture of the WSO2 model consists of five layers as Devices, Communications (MQTT, HTTP), Aggregation (Enterprise Shared Bus and Message Broker), Event Processing and Analytics and Client/External Communications (Web Portal, Dashboard, APIs), which can be correlated with five-layer architecture. However, by introducing cross-cutting layers as Device Manager and Identity and Access Management the model differentiated itself from traditional IoT architectures. Device management layer maintains the list of device identities and map thesis into owners. Identity and Access Management layer handles token issuing and validation, policy management for access control and manages directory of users. More extended version of WSO2 reference model was developed by authors in [34]. The model extended by Service Layer between data aggregation and event processing layer. The layer consists of Resources Management and Service Repository and Discovery services. In addition, to enhance security and privacy in different layers authors introduced a vertical layer which enables to uniquely identify objects and control access to them. Figure 6 presents a visual illustration of a reference architecture proposed in [34].

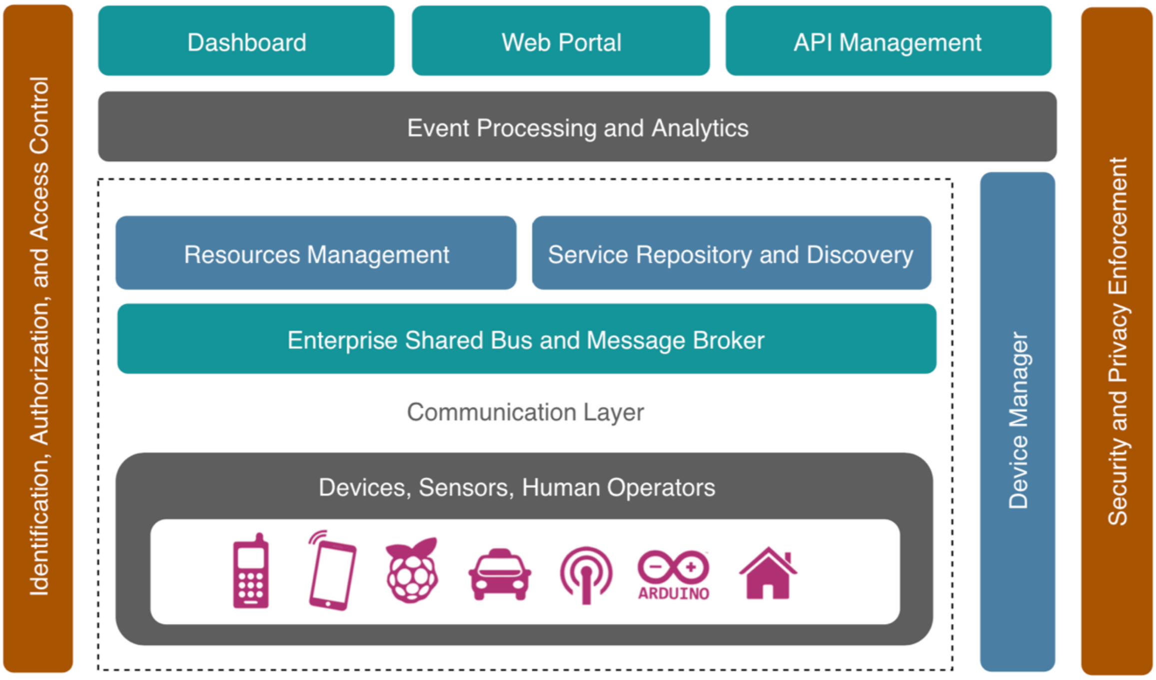


Figure 6. A Reference Architecture for IoT. [34]

2.1.2 IoT Platforms

Having in mind a clear picture of IoT architecture from the previous chapter now we are able to analyse IoT platforms. The IoT platforms consist of a huge number of objects distributed all around the world. It connects edge devices and gateways to cloud services and applications. Indeed, IoT Platform is a central piece in the IoT ecosystem that connects physical world with virtual world. Nowadays, IoT platform functional blocks are a trending field of research. Authors in [7] define three major IoT components such as *hardware, middleware* and *presentation* which basically covers the three-layer IoT architecture discussed at the previous section. Another research states that fully functional IoT system should have six main elements such as *sensing, communication, computation, services, semantics and identification* [35]. In addition, IoT Analytics group proposes a detailed overview of IoT Platform, which consists of 8 major building blocks [36] which is present in Figure 7.

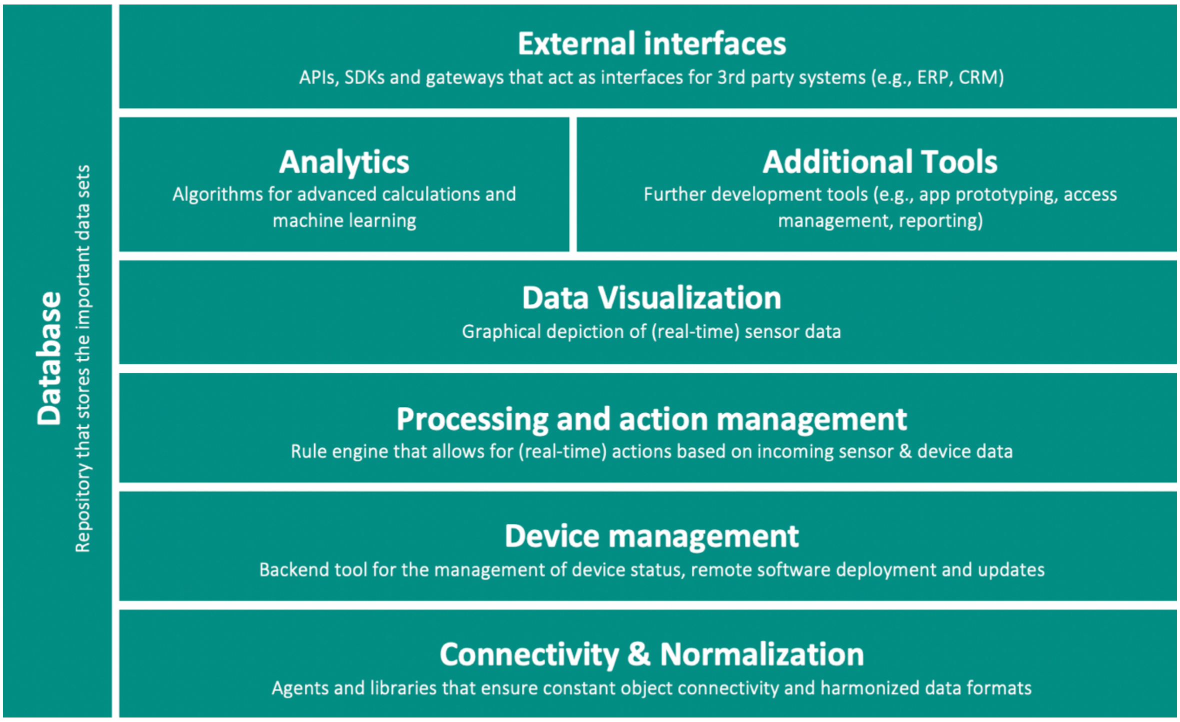


Figure 7. Building blocks of IoT platform [36]

Nowadays a number of IoT platforms is rising rapidly. It is hard to state exact figures; however, different research and analytic groups attempt to identify approximate number of platforms in the market. The most up to date information from IoT Analytics group presents a list of 450 IoT Platforms worldwide operating in different sectors [37]. The same source marks a 25% increase compared to the previous year. Several surveys are conducted by various research groups to assess different aspects of these IoT platforms. It is a time-consuming job to compare all existing platforms in the market, in addition, there is no unified standards to evaluate all platforms. Therefore, researchers select certain amount of the IoT platforms to review according to their pre-defined comparison criterion. Authors in [38] present a survey of 28 platforms according to their application domain. Another research group summarizes 14 publicly available IoT platforms against pre-defined metrics [35]. A survey of platforms for massive IoT is presented in [39], which takes into account metrics such as device management and integration, security, communication protocols, data analytics type and support for visualization. A comprehensive survey and gap analysis of IoT platforms is conducted by researchers in [40] which review around 40 IoT platforms with respect to the support for heterogeneous devices, security and privacy, data processing and data sharing capabilities, support to developers, maturity of an IoT ecosystem, and the availability of dedicated IoT marketplaces.

Taking into account findings from the discussed surveys we shortlisted the most popular platforms which are a subject of review in most of the papers. Table 1 presents shortlisted 10 platforms which are discussed in the majority of related work.

Table 1. IoT platforms comparison.

Platform	Open-source	Architecture	Device communication	Security	Last update	Developer support
AWS IoT [41]	no	cloud-based	MQTT, HTTP1.1	Link Encryption, Authentication (SigV4, X.509)	May 2019	***
Carriots	no	cloud-based	MQTT	unknown	unknown	***
IBM Watson [42]	no	cloud-based	MQTT, HTTPS	Link Encryption, Authentication, Identity management	Jun 2018	***
KAA	Apache license 2.0	unknown	MQTT, CoAP	unknown	Oct 2016	**
MS Azure [43]	no	cloud-based	HTTP, AMQP, MQTT	Link Encryption (SSL/TSL)	May 2019	***
OpenIoT	LGPLv3	decentralized	X-GSN	OAuth 2.0 authentication, permissions and roles	Nov 2015	*
Things Board	Apache license 2.0	cloud-based	CoAP, HTTP, MQTT	Authentication, token request	May 2019	***
Thing Speak	no	centralized/ cloud-based	MQTT, WebSocket	2-level authentication	April 2019	*
Thing Worx	no	cloud-based	WebSocket, AMQP, MQTT, XMPP, CoAP, DDS	Identity Management, Standards (ISO 27001),	Jan 2019	*
Xively	no (except libraries)	cloud-based	Sockets/ WebSocket, HTTP, HTTPS, MQTT	Link Encryption (SSL/TSL)	Sep 2018	**

Commercial IoT platforms provided by world-known companies such as Amazon, IBM and Microsoft are definitely of high standard and excellent support for developers. However, their services come with price and are not within delimitations of this research [41]–[43]. After several years of open availability platforms such as ThingSpeak and ThingWorx are turned into commercial projects [44], [45]. Xively is now part of the

Google Cloud Platform [46]. Another former open-source platform Carriots is acquired by Altair global technology company [47]. OpenIoT open source IoT platform had a huge vision at the start of the project, however, the last release was four years ago [48]. Majority of the dependencies of the platform are outdated and developer support is in a poor level. KAA is one of the popular IoT platforms which has both commercial and open-source versions [49]. However, the open-source version was last updated in 2016 and developer support of the project is in a moderate level. ThingsBoard is relatively new platform which is gaining increased popularity in the recent years in open source community and among researchers [50]–[52]. The platform provides near to real-time developer support and constant releases. In addition, quick installation process, easy-to-use administration interface makes the platform desirable to use for any IoT solution. Taking into account the comparison results, for this research ThingsBoard is selected as an IoT platform of choice.

2.1.3 IoT Application Areas

Potential applications of the IoT are various and diverse, spreading out to all intents and purposes of every-day life of people, businesses and society as an entire. European Research Cluster for Internet of Things (IERC) has a vision of "the major application fields for IoT are the creation of smart environments/spaces and self-aware things for climate, food, energy, mobility, digital society and health applications" [53] Authors in [24] state that a wide range of IoT application domains can be grouped into Transportation and Logistics, Healthcare, Smart Environment and Personal and Social domain. However, IERC has defined a more extended version of IoT application fields which consists of Smart Planet, Smart Cities, Smart Energy, Smart Buildings, Smart Transport, Smart Industry, Smart Health and Smart Living [53]. In [54] IERC researchers presented a list of the most trending IoT application scenarios in 12 different domains:

1. Smart city is relatively more popular domain where IoT is applied to create awareness on status of different buildings, visualize traffic congestion and urban noise as well as to monitor availability of parking spaces. Moreover, waste management, street lights and transportation systems are optimized by adoption of IoT.

2. Smart environment is another key area where IoT enables air pollution monitoring and control, forest fire detection, soil moisture detection and earthquake early detection.
3. Smart water is an area where IoT is applied for studies of water quality in rivers and sea as well as for pipe water leakages and river floods detection.
4. Smart metering area enhanced by IoT with energy consumption monitoring and management in smart grids, solar energy plants control, silos stock calculation and other.
5. Security & Emergencies area applies IoT for access control to restricted areas, liquid detection in data centers and other sensitive buildings, to assess radiation levels and detect explosive and hazardous gases.
6. Retail domain utilizes IoT for NFC payments, smart shopping applications and smart warehouse management.
7. Logistics domain applies IoT for monitoring item location, shipment conditions and storage incompatibility detection.
8. Industrial Control harnesses IoT for indoor air quality and temperature monitoring, automation of vehicle control in mining fields, and etc.
9. Smart Agriculture is enhanced by IoT with soil moisture control, green houses micro-climate control, monitoring of meteorological conditions, and control of compost humidity.
10. Smart Animal Farming applies IoT for offspring care and health anomalies detection, animal tracking and study of ventilation in farms.
11. Home Automation: IoT is applied for monitoring of utility resources consumption, remote control of appliances and home security, and good preservation in museums.
12. eHealth is one the critical areas where IoT can be applied for fall detection of disabled people, control conditions of medical fridges, monitoring of sportsmen health in high performance centres or patients conditions in hospitals as well as to detect ultraviolet radiation and warn people about peak hours [54].

This work lies within the bound of Smart Environment domain and focuses on monitoring and visualizing outdoor air pollution.

To summarize, this section discussed the notion of IoT, reviewed existing reference architectures and surveyed major IoT platforms. Moreover, application areas of IoT and the most trending domains are presented. The most important takeover of the chapter is the chosen IoT platforms as a result of the survey. A specific list of criteria was defined in order to select the most appropriate platform for this research. The next section reviews context-aware computing, which enables optimal processing of the raw data from the IoT devices.

2.2 Context-Aware Computing

Currently many web, mobile, desktop applications use context-aware approach to the Internet of Things. The ultimate goal of the context-aware computing is to support the appropriate response to the users and the environment. Therefore, the context-aware applications have an ability to adapt to the user's situation without the user being distracted. The context-aware computing has been widespread after the introduction of the term ubiquitous computing by Mark Weiser in 1991 [55]. A paper by Schilit and Theimer used the term context-aware computing for the first time in 1994 [56]. The research focus is on providing context-aware location information of administrative entities.

In order to implement context-driven applications as mentioned above, it is crucial to understand context and its evolution. The following section presents definitions of context and its different characteristics.

2.2.1 Defining Context

Numerous researchers attempt to define context in their work. In the definition given by Ryan et al. [57] context can be seen as user's identity, current location, environment, and time. Dey et al. [58] consider as context information as the user's emotional state, location, orientation, date, time and surrounding objects. Some papers use synonyms of the context such as an environment or a situation [59]–[62].

Abowd et al. [10] present a review of these definitions and discuss weaknesses. With highlighted limitations of the previous attempt the researchers present a broader definition for context as following:

“Context is any information that can be used to characterize the situation of an entity. An entity is a person, place, or object that is considered relevant to the interaction between a user and an application, including the user and applications themselves [10].”

In this research we accept definition of the context by Abowd et al. since it is more generalized definition that can be found in the literature. After clarifying the definition of the term context, now we are able to determine what is context awareness.

Schilit and Theimer were the first to introduce the term context-awareness [56]. Numerous researchers refer to context-aware applications as the ones that based on the context of the user and application itself dynamically adapt their behaviour [63]–[66]. Abowd et al. [10] present a review of papers which refer to context-aware by synonyms such as reactive, adaptive, situated, responsive, context-sensitive and environment-directed. Abowd claims that definition provided earlier are too specific and restrictive to identify context awareness of applications. Therefore, they propose the following definition: “A system is context-aware if it uses context to provide relevant information and/or services to the user, where relevancy depends on the user’s task [10].” Researchers in [67] define context-awareness’ five major elements such as context acquisition, modelling, reasoning, dissemination and context adaptation. The main focus of context acquisition is on context data collection from different types of sensors, then this context data is converted to a machine-readable form with context modelling. Next, context reasoning is used to reason high level situation awareness from a low-level context. Afterwards, context is presented to a user or an environment via context dissemination. Lastly, context adaptation focuses on selection of relevant services for a user according to the context.

A more simplified context lifecycle is presented in [68], which is based on a review of the previous works and contains all essential phases. The proposed context lifecycle consists of four phases including context acquisition, context modelling, context reasoning and context dissemination. The phases have the same focus as in [67], however, context adaptation phase is not considered.

A good context modelling reduces the complexity of an application and enables to provide relatively accurate context-aware service. Moreover, context modelling is necessary to have a common picture of a system and its components. In addition, context modelling helps to deal with mobility and heterogeneity of the context sources. Many context modelling approaches has been proposed over the last decades with evolvement of the context-aware computing. The survey in [68] illustrates six most widespread context modelling techniques such as mark-up schemes, key-value, logic based, object-based, graphical based, and ontology-based modelling. The paper presents a comparison of these approaches as well. However, there is no standard for context modelling and choice of approach is subjective decision. [69] claims that all context models have their strength and weaknesses. For this research Context Spaces Theory is used to model a context. The definition, main components and benefits of the model are discussed in the following section.

2.2.2 Context Spaces Theory

Context Spaces Theory (CST) is a conceptual framework for context-aware systems introduced by Padovitz et al. [70]. The main idea of the approach is to represent context as a multidimensional space. In order to understand the CST, it is necessary to introduce the following set of new terms.

A *context attribute* (denoted as a_i) is any type of data that is used to reason a context. A context attribute can be a reading from sensors or derived from other context attributes. For example, readings from a temperature sensor can be a context attribute.

An *application space* (denoted as $\mathfrak{R}$) is a multidimensional space that is composed of an entire set of relevant context attributes. Each context attribute is an axis of the application space and a specific value on the axis is referred as a context attribute value.

A *context state* (denoted as C_i) is a collection of all relevant context attribute values at specific time t. A context state can be illustrated as a point or subspace in space.

$$C_i = (a_1^V, a_2^V, a_3^V, \dots, a_n^V)$$

For example, a context state can be made up from context attributes such as light level(a_1^V), temperature(a_2^V) and humidity(a_3^V).

A *situation space* is a subspace of application space and represents a reallife situation (denoted as S_i). Situation space is a subspace of application space and contains a set of regions of context attribute values.

$$S_i = (a_1^R, a_2^R, a_3^R, \dots, a_n^V)$$

For example, if we assume a situation space for a comfortable indoor environment, acceptable region of values for a room temperature can be between 22°C to 24°C and the range of values for relative humidity can vary from 40% to 60%. Figure 8 shows a visual illustration of context space and its elements.

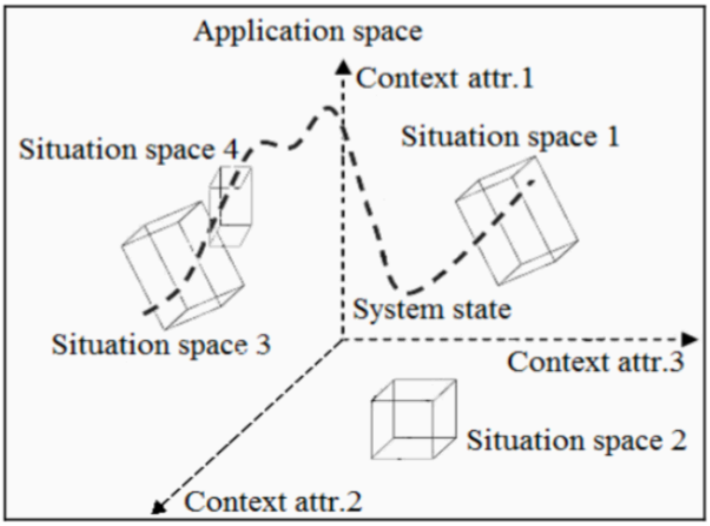


Figure 8. Context Space illustration. [70]

The CST provides an abstraction which enables to achieve a coherent context representation. In addition to the aim of comprehensively and insightfully representing context, the theory addresses challenges of reasoning about context in uncertain environment [71]. Since this thesis aims to implement context aware system which uses uncertain raw environmental data as one of the data sources, the use of the CST can help with accurate context modelling.

To sum up, this section discussed a briefly context-aware computing, highlighted different definitions of context and context-awareness, reviewed context lifecycle as well as introduced CST on the basis of which the thesis will be implemented. As it was stated before the main focus of this thesis is to implement a context-aware visualization system for outdoor air pollution use case. With the well-presented big picture of the context-aware system we transit to the background review of data visualization at the next section.

2.3 Data Visualization

Data visualization has an ultimate goal of making data more understandable and interpretable for humans. According to authors in [72] data visualization is defined as "the representation and presentation of data that exploits our visual perception abilities in order to amplify cognition." As it was mentioned before [8], [25], there are billions of devices that are connected to the Internet and the number is growing exponentially. The amount of data generated by the smart devices already reached a huge extent [73] and mostly cannot be interpreted without adequate data visualization methods. A report by researchers in [74] presents a significance of the data visualization for decision-making, improved information sharing, provision of self-service capabilities to end users and other. On the other hand, results in [75] prove that the resulting image of different data presentation techniques applied to the same data might differ vastly. Therefore, relevant techniques have to be applied depending on the current context or situation.

2.3.1 Context-driven Visualization

The variety of existing visualization techniques and their endless configuration options makes it a hard and tedious procedure to choose the most suitable representation approach even for experts.

Several studies attempt to apply context-aware approach for the data visualization. A comprehensive system for the context-driven data presentation is implemented by Eissele et al. [76], where authors consider device performance and connectivity as a context to provide visual data. Authors in [77] demonstrate a visualization framework for context-aware systems, which focuses on efficient communication and parallel processing. The researchers claim that mobile devices lack a computational power to perform complex tasks and provide context-aware services. However, with the use of stream processing which supports parallel computation on distributed and shared memory multiprocessors authors demonstrate effective context-aware visualization approach. Another work in [78] illustrates a framework for smart cars, which enables to interpret and disseminate context to provide context-aware visualization. Context-aware approach is used to visualize traffic accidents in [79], where focus was not on the user interface but the content of data to be visualized. The primary challenges of context-aware visualization services implementation are discussed in [80]. The paper points out run-time issues of the correlation of context elements changes and simultaneous reconfiguration of the user interfaces, interoperability of heterogeneous visualization services, information sharing throughout different services and integration of separate services into one homogenous view. As a solution of the aforementioned problems, the authors present a framework called visualization mosaics

(ViMos), which generates user interfaces dynamically. The framework applies context-awareness to visualize adapted interfaces. The generation of user interfaces comprises of several steps such as acquisition of the context, selection of candidate data, selection of candidate design pattern and information pieces and finally incorporation of all awareness elements.

To summarize, some of the previous studies attempt to adapt their content according to the user interface and device characteristics, while others provide dynamically changing interfaces. However, all studies agree that there are a great number of issues to be considered, when implementing context-aware visualization solutions, such as user preferences, user's current task and surrounding environment status.

2.3.2 GIS Data Visualization

The previous section discussed different aspects of context-aware visualization. Since this thesis focuses on context-aware visualization of air pollution maps, it is necessary to review previous works on location-based systems.

Recently Geographical Information Systems (GIS) is increasingly being applied for various geospatial disciplines. According to Aronoff [81], GIS is a computer-based system that provides the following four capabilities to handle *georeferenced data* such as (i) data capture and preparation, (ii) data management, (iii) data manipulation and analysis, and (iv) data presentation. Georeferenced data or spatial data mean data that contains position values, such as (x,y) coordinates [82].

GIS is applied to visualize spatial data in different fields. Example giving, in [83] authors use GIS to visualize statistical information on population density distributed geographically. The study proposes a model of 3D space, where two dimensions are used for coordinates and one for population density. An investigation of 3D visualization of GIS data based on context-sensitive middleware is presented in [84]. However, the study can be considered as a preliminary discussion of context-aware approach adoption for the GIS data visualization due to the minimum consideration of a context. Another study presents GIS data visualization in the field of Augmented Reality [85]. This research aims to use GIS for outdoor air pollution visualization as it is a perfect fit for the temporal and spatial data representation.

In conclusion, this section presented the subject of data visualization, its theoretical definitions and practical approaches. Moreover, as important areas related to this research, context-driven visualization proposals and GIS data visualization methods are reviewed. The research utilizes GIS to visualize spatial and temporal data. A gap on context-driven visualization is identified and this thesis aims to contribute to it with adopting user preferences as a context for the data visualization. With a background reviewed on context-aware data visualization, now we can discuss about environmental data. The next section presents a state-of-the-art in the air pollution monitoring and application of context-aware computing and IoT to environmental monitoring.

2.4 Ambient Air Pollution

This section of paper discusses dynamics and trends of air quality, health and environmental risks caused by ambient air pollution as well as benefits of visualizing and creating awareness on pollution. Methods to monitor and assess air pollution levels are also reviewed.

Air pollution is a rapidly evolving concern in the past decades with the growth of pollution sources worldwide. According to the European Environment Agency (EEA) pollutants released to the air from a wide range of sources including transport, agriculture, industry, waste management and households [1]. Rapid urbanization and industrial growth exacerbate the problem and the pressure felt severely in big cities. However, air pollution does not respect borders. Air pollutants and heavy metals are carried by wind, contaminating water and soil far from the origin [2]. Therefore, air pollution is not a problem of solely developing countries but a global burden which affects all parts of society.

According to the World Health Organization (WHO), 92% of population in our planet lives in the areas that exceed ambient air quality limits. In addition, the report states that air pollution is the largest environmental risk to health, being responsible to each ninth deaths per year. Moreover, statistics show that outdoor air pollution alone is a cause of 3 million deaths annually [3], [86]. Taking into consideration statistics on ambient air pollution mortality and health risks, air pollution has been defined as a health priority and has been included to the Sustainable Development Agenda [12].

2.4.1 Air Pollution Monitoring

The previous section discusses the importance of creating an awareness on air pollution. Environmental agencies around the world making attempts to provide air quality information in an easily understandable form as the weather forecast. The most generic approach in this effort is Air Quality Index (AQI). The AQI is utilized to provide air quality information and health risks for different levels of pollution [87].

The US Environmental Protection Agency (EPA) has established AQI value range from 0 to 500 as a standard for reporting daily air quality. With the higher AQI values the greater is the air pollution level and health risks. The values of AQI are classified into 6 categories such as good, moderate, unhealthy for sensitive groups, unhealthy, very unhealthy and hazardous. Table 2 illustrates the AQI values, categories, their meaning and respective action to be taken in order to protect public health as well as colour codes used to indicate different air pollution levels.

Table 2. AQI values, meaning and actions to protect health. [88]

Category	AQI	Meaning	Actions to Protect Health
Good	0 to 50	Satisfactory air quality	None
Moderate	51 to 100	Acceptable air quality	Limited outdoor activities for extremely sensitive groups
Unhealthy for Sensitive Groups	101 to 150	Sensitive groups feel discomfort	People with lung diseases, children and elder adults should limit outdoor exertion
Unhealthy	151 to 200	Everyone experiences discomfort, sensitive groups might have health issues	People with lung diseases, children and elder adults should limit outdoor exertion
Very Unhealthy	201 to 300	Emergency conditions	People with lung diseases, children and elder adults should avoid outdoor exertion.
Hazardous	301 to 500	Hazardous emergency conditions	Everyone should avoid outdoor activites

The EPA developed standard formula to calculate AQI from raw measurements. AQI of a pollutant is calculated by the following formula:

$$I_p = \frac{I_{Hi} - I_{Lo}}{BP_{Hi} - BP_{Lo}} \left(C_p - BP_{Lo} \right) + I_{Lo}, \qquad (1)$$

where I_p is the air quality index for pollutant p, C_p is the truncated concentration of pollutant p;

BP_{hi} and BP_{lo} are the concentration breakpoints that are greater than or equal to and less than or equal to C_p respectively; I_{hi} and I_{lo} are the AQI values corresponding to BP_{hi} and BP_{lo} respectively. First we calculate AQI for each pollutant and then the highest AQI value is used as an overall AQI. The formula below shows the calculation of overall AQI:

$$I = max(I_p), \qquad (2)$$

where I is an overall AQI and I_p is an AQI of a specific pollutant.

Table 3 illustrates the values of major air pollutants such as carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), particulate matter ($PM_{2.5}$) and sulphur dioxide (SO_2) and respective to the AQI categories.

Sensitive groups to O_3 include people with lung disease, older adults, children, people who work actively outdoors. $PM_{2.5}$ is hazardous for people with lung or heart disease, children, older adults, and people of lower socioeconomic status are the groups most at risk. NO_2 and SO_2 are harmful for children, older adults and people with asthma. For high concentrations of CO is dangerous for people with heart diseases [88].

Even though AQI standards presented by US EPA are well-known and widely used in different countries, there exists a variety of other standards adopted in national or regional scales. For example, in 2017 European Environment Agency (EEA) launched a new European Air Quality Index [89]. EEA takes measurements of five key air pollutants such as nitrogen dioxide, ozone, sulphur dioxide and two types of particulate matter particulate matter. The levels of pollution are classified into five categories including good, fair, moderate, poor and very poor. Table 4 demonstrates the values of pollutant according to the classification and colours used to differentiate the pollution levels.

Table 3. AQI pollutant-specific categories. [88]

Category	AQI	O_3 (ppm) 8-hour	$PM_{2.5}$ ($\mu m/m^3$) 24-hour	CO (ppm) 8-hour	SO_2 (ppm) 1-hour	NO_2 (ppm) 1-hour
Good	0-50	0.000-0.054	0.0-12.0	0.0-4.4	0-0.035	0-0.053
Moderate	51-100	0.055-0.070	12.1-35.4	4.5-9.4	0.036-0.075	0.054-0.100
Unhealthy for Sensitive Groups	101-150	0.071-0.085	35.5-55.4	9.5-12.4	0.076-0.185	0.101-0.360
Unhealthy	151-200	0.086-0.105	55.5-150.4	12.5-15.4	0.186-0.304	0.361-0.649
Very Unhealthy	201-300	0.106-0.200	150.5-250.4	15.5-30.4	0.305-0.604	0.605-1.249
Hazardous	301-500	>0.200	250.5-500.4	30.5-1004	0.605-1.004	1.250-2.049

Table 4. European AQI standards. [89]

	$PM_{2.5}$ ($\mu m/m^3$)	PM_{10} ($\mu m/m^3$)	NO_2 ($\mu m/m^3$)	O_3 ($\mu m/m^3$)	SO_2 ($\mu m/m^3$)
Good	0-10	0-20	0-40	0-80	0-100
Fair	10-20	20-35	40-100	80-120	100-200
Moderate	20-25	35-50	100-200	120-180	200-350
Poor	25-50	50-100	200-400	180-240	350-500
Very poor	50-800	100-1200	400-1000	240-600	500-1250

Since a part of our experiments is held in Melbourne, we have reviewed standards in Australia. We use national ambient air quality standards are defined by Australian National Environment Protection Council [90]. Table 5 presents information on Australian AQI categories, value ranges and interpretation of categories.

Table 5. Australian AQI standards. [90]

Category	AQI range	Description
Very good	0-33	Very good air quality, no health risks
Good	34-66	Good air quality, little or no health risks
Fair	67-99	Acceptable air quality. A little health concern for sensitive groups
Poor	100-149	Unhealthy air quality for sensitive groups
Very poor	>150	Unhealthy air quality for everyone

EPA claims that AQI is an essential way of carrying scientific and medical advice to the public in a very interpretable form [87]. Indeed, AQI provides a comprehensive way to create awareness on air pollution. Therefore, in this research we will use AQI for context modelling. All three AQI standards discussed above, namely Australian, European and US are considered as the system adopts context-awareness. The next section discusses the value of creating awareness on air pollution and how it can contribute for sustainable development.

2.4.2 The Role of Air Pollution Monitoring

In the previous sections we discussed statistics on air pollution and possible ways to measure the pollution levels. This section reviews importance of air quality monitoring and its benefits.

Human exposure to air pollutant may cause different health issues depending on the type of pollutant, duration of exposure and the toxicity level of the pollutant. The WHO air quality guidelines for Europe explicitly explain health effects of various pollutants [4]. The study in [91] presents a review of works focused on adverse effects of air pollutant to respiratory, cardiovascular, nervous, urinal and digestive systems of a human organism. The most widespread health effects observed by different investigations include: asthma attacks, reduced lung functioning, development of respiratory diseases and premature death [5].

Along with the human health effects air pollution contributes to deterioration of environment. The environmental effects of air pollution include eutrophication, acid rain, ozone depletion, crop damages and global climate change and others. Smog is a

widespread term referred to variety of air pollution events mainly in large cities. Acid rain is another adverse effect of the air pollutants. Acid rain affects forested landscapes, soil and aquatic ecosystems. Sulphur dioxide and ozone are the main contributors of smog formation. The most crucial result of air pollution is the climate change which is caused by carbon dioxide which causes the greenhouse has effect and contributes global warming [92]. Major sources of air pollution vary depending on the region, typical local industry and size of the population. For example, in China major pollution comes from industrial coal, transportation, residential biomass burning and other, while in India the major sources of outdoor air pollution are residential biomass burning and anthropogenic dust [93]. The major source of outdoor air pollution addressed in Europe is transportation [94].
Atmospheric environmental protection, response policies, health impact and risk assessment as well as air pollution modelling is impossible without the quantitative information of air quality. The aim of air quality management is to monitor and control ambient air quality so that it is safe for the public health and environment. In order to assess status of the air, current air quality must be monitored. Creating awareness on air pollution can contribute to both reducing exposure and decreasing emission levels. Moreover, the air quality information is required by scientists, regional and national planners and policy-makers to support them in taking savvy decisions on managing and controlling the environment. Air quality monitoring provides the necessary scientific basis for developing policies, setting objectives and planning enforcement actions [5]. Figure 9 presents the role monitoring in air quality management.

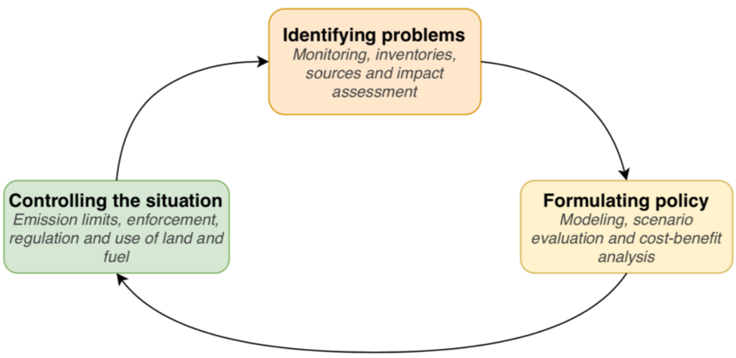


Figure 9. The role of monitoring in air quality management. [5]

Despite the importance of measurements, in many cases, monitoring solely is not enough for the purpose of fully identifying population exposure in the environment. Therefore, as mentioned before, monitoring needs to be supported by other assessment techniques such as modelling, context-awareness and visualization of the measurements. The next section of the thesis reviews state-of-the-art in the existing context-aware air pollution visualization solutions.

2.5 State-of-the-art on Context-Aware Air Pollution Visualization

With the knowledge on importance of monitoring air quality and creating awareness on pollution levels, this section aims to review the existing proposals applied for indoor and outdoor air pollution monitoring. Numerous researches are conducted in the area of air quality monitoring and for this study 20 state-of-the-art literature are selected to review and identify open research questions. In order to compare existing air quality monitoring and visualization solutions a taxonomy is developed. Table 6 illustrates the taxonomy for evaluation and gives a brief description on each property.

Table 6. A taxonomy to compare the state-of-the-art.

	Taxonomy	Description
1	Environment type (ET)	Indoor(I), Outdoor(O)
2	Physical Air Properties (PAP)	Air Exchange Rate (AER), Humidity(H), Temperature (T), Relative Pressure (RP), Wind (W)
3	Chemical Air Properties (CAP)	CO, CO2, H2S, NO2, O3, PM, PM2.5, PM10, SO2, Not Specified(N/S)
4	Data Acquisition (DA)	Sensors, Meteorological Station (MS), Pollution Monitoring Station (PMS), Datasets, Crowd-sensing, Images, Application Programming Interfaces (APIs)
5	Data Processing (DP)	Humidex (Hx), Air Quality Index (AQI), Other (specify)
6	Context attributes (CA)	Location, Time, Environment, Activity, User Profile, Data Visualization, Other (specify)
7	Data Visualization (DV)	Charts, Numbers, Maps, Other (specify)

First of all, each solution is developed for a certain *environment type* such as indoor, outdoor or both. Emissions are affected by meteorological conditions, a number of chemical and physical properties. Therefore, different existing works consider a variety of *physical air properties* such as temperature, humidity, relative pressure, air exchange rate and ventilation and wind speed and others. The *chemical air properties* (air pollutants) considered in the existing literature also vary depending on the importance of pollutant in the investigation area or availability of an infrastructure. After defining which physical and chemical characteristics are considered, it is important to know the *data acquisition* method. Some solutions set up their infrastructure and use live data coming from sensors and sensor networks, while others might use available data from national meteorological stations or even open dataset from the Internet. *Data processing* techniques in the literature are highly heterogenous, therefore, adding it to the taxonomy also gives a valuable information on similarities and differences between the existing works and our solution. Since this thesis aims to adopt context-aware approach, list of *context attributes* considered in the studies also included in the taxonomy. However, not all solutions specify their context-awareness by using this term. Nevertheless, most of the systems are, at least, location and time-aware. Some systems even consider user's health issues. Therefore, we decided to identify context attributes considered in the works, rather than binarizing it by saying the system is either context-aware or not. Moreover, this thesis focuses on context-driven *data visualization*. Therefore, if any system considers user or device characteristics as a context for data visualization, we will show data visualization as a context attribute. Lastly, as one of the key areas for this thesis, we compare data visualization approaches considered in the existing studies. Table 7 presents a comparison of 20 state-of-the art literature according to the aforementioned taxonomy.

A. Environment type

According to [95] average person spends 80% of their time indoors. Therefore, many of the existing studies focus on indoor air quality monitoring. For example, [96]–[99] and [100] present different solutions for indoor air quality monitoring, prediction and control. However, recent statistics from WHO on air pollution illnesses and mortality show that number of deaths caused by outdoor air pollution is more than 3 million [86]. The number roughly is the same as the household pollution mortality rate.

Table 7. The state-of-the-art literature comparison.

Research	ET	PAP	CAP	CA	DA	DP	DV
[101]	O	-	O_3, PM	-	crowd-sensing	N/S	heatmap
[102]	I, O	-	-	-	crowd-sensing	AQI	heatmap, AQI indices
[103]	I, O	H, T	12 pollutants (N/S)	-	sensors	AQI	AQI indices
[96]	I	AER	CO_2	User profile	sensors	AQI	AQI indices
[104]	O	H, T, RP, W	CO, NO_2, O_3, $PM_{2.5}$, PM_{10}, SO_2	User profile	MS, PMS	AQI	red coloured pollution areas
[105]	O	-	N/S	-	datasets	bidirectional route traversal	pollution-based routes
[106]	O	-	N/S	-	MS, PMS	N/S	Coloured pollution levels
[107]	O	H, T	CO, NO_2, H_2S, O_3	-	PMS	AQI	Pollution indices
[108]	I, O	H, T, RP	CO, NO_2, O_3	User profile	crowd-sensing	N/S	Charts, coloured pollution levels and indices
[109]		-	CO, NO_2, O_3, $PM_{2.5}$, PM_{10}, SO_2	-	PMS	N/S	Pie charts
[110]	I, O	N/S	PM	-	sensors, PMS	AQI	Line graph, AQI indices and colours
[97]	I	AER, H, T	CO_2	+	sensors	Linear regression	Coloured pollution levels and indices
[111]	O	H, T, VOC	CO_2	-	sensors	-	Line graph
[98]	I	H, T	CO, CO_2, NO_2, O_3, PM, SO_2, VOC	location, time, user profile, pollutant type	sensors	AQI, heuristics, calibration	Time-series charts
[99]	I	H, T	PM	location, time, user profile	sensors	AQI, situation reasoning	AQI indices
[100]	I	H, T, AER	-	environment, location, time	sensors	-	-
[112]	O	-	N/S	location	sensors	smart-mapReduce	3D pollution maps
[113]	O	H, T	NO_2, SO_2	location	datasets	ANN	pollution hot spots
[114]	I, O	-	CO, NO_2, $PM_{2.5}$	user profile	crowd-sensing, sensors	calibration	pollution maps
[115]	I, O	H, T	$PM_{2.5}$	location, time	crowd-sensing, sensors, APIs	Gaussian Process, Bayesian Methods	heatmap, charts, pollution-based routes

Numerous works propose systems to monitor and predict ambient air pollution. Studies in [104], [105], [111] demonstrate various solutions for outdoor air quality, while other papers such as [103], [108], [114] and [115] consider both environment types.

B. Physical Air Properties

In addition to air pollutants different air quality characteristics can affect pollution levels of environment. For example, air exchange rate inside a room or wind outside enable air movement, consequently, decrease concentration of pollutants of an area. Moreover, [99] considers temperature and humidity to calculate humidex introduced in [116] which is an approach to estimate human discomfort due to heat and humidity levels. From the reviewed literature [96] considers air exchange rate (AER) and [113] takes into account room ventilation to calculate indoor air quality, whereas [104] considers wind speed when measuring outdoor air pollution rate.

C. Chemical Air Properties

In order to accurately measure air pollution rate, a range of pollutants must be considered. For example, US Environmental Protection Agency (EPA) covers six main pollutants to calculate Air Quality Index (AQI) and sets its limits on human health [117]. European Environment Agency proposes European Air Quality Index which is based on five major pollutants that harm people's health and the environment such as nitrogen dioxide (NO_2), ground-level ozone (O_3), particulate matter ($PM_{2.5}$ and PM_{10}), and sulphur dioxide (SO_2) [118]. [104], [109] and [98] cover majority of the pollutants mentioned in the above standards, while [112] consider 12 pollutants. However, pollutant types are not specified in several studies such as [105], [106] and [100]. Overall, findings from review show that majority of the studies consider carbon oxides or particulate matter which demonstrate significance and widespread nature of the pollutants.

D. Context-Awareness

Increasing number of IoT devices and their computing capacity bring a new benchmark for smart devices. Nowadays, devices are expected to give relevant information according to user’s current situation. This is the main task of context-aware applications. In spite of the fact that a huge number of solutions proposed in the area of environmental monitoring, only few consider context-aware approach. Most papers consider basic context information such as current location, time and pollutant type. [112] and [113] provide only location-based information, while [115] considers time. [98]–[100] consider more context information such as environment and user's personal health features, however, all three researches oriented on indoor air quality.

Assessment of exposure to air pollutants is a reasonable measure of health risks. However, the same dose of pollution may affect each person differently. Therefore, they may experience dissimilar health effects. Review findings show that a few papers consider user's health problems and age when providing air quality status for indoor environments. However, there is still a research gap on applying context-aware approach to outdoor air pollution monitoring. Moreover, user's visual perception context such as eyesight impairments, colour-blindness and others are not considered for data visualization.

E. Data Acquisition

Variety of data acquisition methods are used in different studies. The most common practice is instalment of different gas sensors or sensor nodes with several built-in sensors. For example, in [103] sensor node with 12 built-in sensors is equipped, while authors in [96] and [99] use individual pollutant sensors. [105], [106] and [113] work with historical air pollution datasets and [106] further considers traffic datasets to estimate more accurate pollution rates. Crowd-sensing is another widespread approach to monitor air pollution. For example, authors in [101], [102] collect data from participants, whereas [114] collects data from both, sensors and crowd. Open-source data, national weather and pollution monitoring centers and internet-connected monitoring stations are other forms of data sources in the literature [104], [106], [107], [115].

F. Data Processing

Calculation of Air Quality Index (AQI) is the most common approach to process air pollution data and provide human-readable interpretation of raw values [96], [102]–[104]. [96] to estimate air quality value uses Bayesian room localization model. [115] presents a cloud-based air quality analytics engine with inference and calibration models. [98] introduces a smoothing algorithm which prevents sensor errors and uses an aggregation algorithm which enables less power consumption and decreases network traffic.

G. Data Visualization

Many researches already proven importance of data visualization to understand trends and make decision over a given dataset. For example, in [75] authors use datasets with identical statistical parameters to generate dissimilar graphs and demonstrate importance of graphical representation method. There is no single standard visualization approach for air quality data, therefore, methods vary from study to study. Majority of papers present numeric indices for air quality [96], [103], [104], where several of them illustrate severity of pollution with respective colours (i.e. good-green, bad-red) [97], [110]. Moreover, in [106] authors provide additional meaning by using descriptive words such as "good", "non-critical", "warning", "alert", or "alarm". [101], [102] and [115] visualizes data with pollution heatmaps. [105] and [115] provide pollution-based routes from origin to destination. [109]–[111] and [98] visualize real-time and historical data with line charts. Review findings show that diversity of visualization methods can be used to present air pollution data, however, there is a little justification of the methods chosen. Moreover, user's preferences and vision impairments are not considered when providing visualization services. Even though there is an attempt of applying context-aware approach in the field of data visualization as discussed in the previous sections, there are still open research areas on adopting user context when visualizing environmental data.

2.6 Summary

This chapter of the thesis discussed IoT paradigm, presented common IoT architecture and reference models and reviewed popular IoT application areas. Moreover, comparison of IoT platforms was conducted to justify IoT platform of choice for this thesis. The chapter also reviewed definition of context and context-aware computing as well as introduced CST, context modelling approach chosen for this thesis. Definition of data visualization and common practices also presented. Context-driven visualization and spatial data visualization were discussed. Since the thesis focuses on air pollution use case, an extensive review of air pollution causes, and effects was conducted. The role of air quality monitoring was studied. Moreover, state-of-the-art literature review was presented in the area of context-aware air pollution visualization. Based on the results of the of the assessment of the related work several conclusions were made. First, there is a small consideration of user context in data visualization. Fewer papers apply context-aware approach for air pollution monitoring and visualization. There is a small justification of data visualization method chosen for air pollution data illustration. Applications proposing air pollution-safe routes do not consider user context to reason situation at each route but are based on main air pollution standards for healthy people. To address these issues in the state-of-the-art literature, we attempt to provide a generic context model to fill the research gaps on incorporating context-aware air pollution visualization and providing users with personalized pollution-safe routes. Our context model reasons current situation that include AQ parameters such as particulate matter and other toxic gases and user profile data such as heart and lung diseases.

3 CONTEXT-AWARE AIR POLLUTION VISUALIZATION MODEL

This chapter presents a model of a context-aware air pollution visualization system and its context modelling and situation reasoning aspects.

3.1 Context Modelling

The conclusions evolved as the result of the literature review demonstrate a research gap on air pollution visualization adopting context-aware approach.

The main objective of this research is to implement a context-aware system for outdoor air pollution visualization. As it was discussed in the previous chapter, in order to implement a context-aware system, first of all, context needs to be modelled. There exists variety of context modelling approaches, however, for the specifications of this thesis Context Spaces Theory (CST) was chosen [70]. The CST provides an abstraction which enables to achieve a coherent context representation. In addition to the aim of comprehensively and insightfully representing context, the theory addresses challenges of reasoning about context in uncertain environments. Therefore, for the environmental monitoring use case, where uncertainty of sensor data is relatively high, using the CST for context modelling is a reasonable choice.

The building blocks and main definitions of CST such as context attribute, application space, situation space and context state are reviewed in the previous chapter. In order to build a context-aware model for air pollution visualization we first define *context attributes* of the system which are used to reason a context. The next, we identified *application space*, which is an entire set of relevant context attributes. Afterwards, *situation spaces* were defined which represent real-life situations. Situation reasoning is based on the *context state* which comprises of all relevant context attribute values at this specific time.

Figure 10 presents an example of application space which considers context attributes such as CO_2, $PM_{2.5}$, distance and user id.

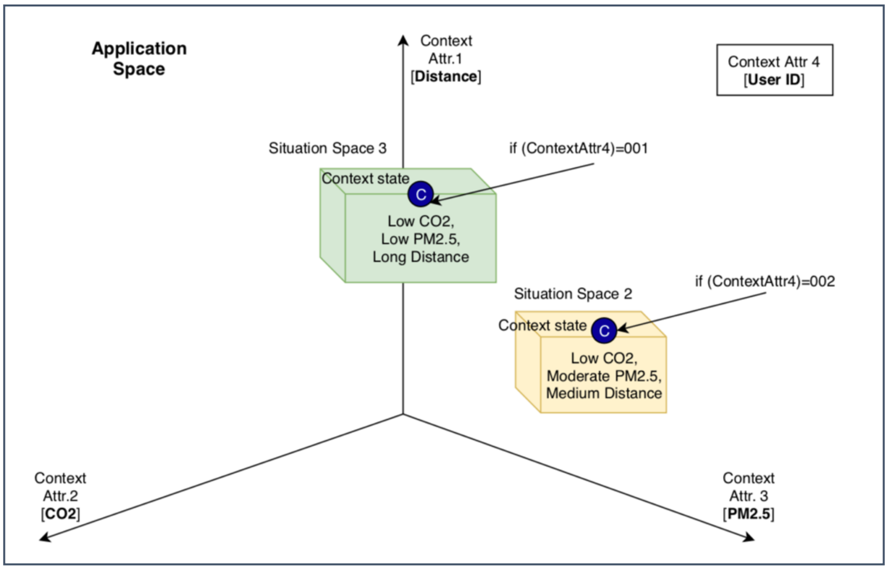


Figure 10. Application Space example based on CST.

The illustration presents two situation spaces where major context is user's sensitivity to $PM_{2.5}$. For the user with id 001, who is not sensitive to $PM_{2.5}$, shortest route with moderate $PM_{2.5}$ value is proposed. However, the user with id 002 is sensitive to $PM_{2.5}$, therefore, route with longer distance but low $PM_{2.5}$ pollution levels is suggested.

The next section present context attributes of the proposed context-aware system for air pollution visualization.

In order to model context using CST, first of all, *context attributes* must be defined. The context attributes of this research are classified into four categories such as general, air quality, data visualization and user profile. Table 8 illustrates a list of context attributes and their respective category.

Next, we give a description of each category and related context attributes.

A. Generic context attributes give general description on user's current situation such as time and location.

- **Current location.** This attribute represents current location of the user's query for air pollution information. Current location is defined by coordinates of latitude and longitude, however, using additional APIs user is provided via comprehensive location names. For example, user can show Deakin University as his current location, but system converts it to -37.848063 latitude and 145.114903 longitude.

- **Destination.** This attribute represents the destination, where user wants to arrive. The destination also defined with latitude and longitude values. Destination also can be shown using user-friendly names as on the example of the current location.
- **Time.** This attribute represents current time of the user's query for air pollution information. This attribute is important to acquire up to date information and provide real-time context updates.

Table 8. A list of selected context attributes.

Category	Context attributes
Generic	1. Current Location 2. Destination 3. Time
Air Quality	1. AQI 2. Pollutant type 3. Pollutant value
User Profile	1. User ID 2. Age 3. Pollutant sensitivity level
Data Visualization	1. Colour blindness

B. *Air Quality context attributes* describe air quality in the user's current environment.

- **AQI.** In order to identify health concern of user to air pollution levels AQI needs to be calculated from the readings of gas sensors.
- **Pollutant type.** Since this research is considering more than one pollutant in order to identify pollution levels, pollutant type it is important to consider pollutant type as an attribute.
- **Pollutant value.** This attribute provides information on the last available reading of the respective pollutant type.

C. *User Profile context attributes* provide personal information about user's age, sensitivity to each pollutant type as well as pre-defined unique id.

- **User ID.** This context attribute is necessary to store user specific data and provide context aware service to the user.
- **Pollutant sensitivity level.** This attribute defines user's personal sensitivity to each pollutant.

- **Age.** This attribute is used to identify sensitivity of a user to the pollution levels. According to EPA, less than 18 year old children and elderly over 65 years are treated as sensitive groups to air pollution [119].

D. Data Visualization context attributes describe user's specific needs for different data visualization techniques.

- **Colour Blindness.** This context attribute provides information on user's ability to differentiate colours assigned for AQI levels. In case, if user has colour vision deficiency, specific colours should be used in order to provide user with meaningful information.

Table 9 provides a detailed information on context attribute value types, a range of all possible values and presents examples.

Table 9. Context attributes, their value types and ranges.

Context attribute	Value type	Value range	Example
Current Location	Pair<Double, Double>	Pair <[-90,90], [-180,180]>	<-37.5, 145.11>
Destination	Pair<Double, Double>	Pair <[-90,90], [-180,180]>	<-37.82, 144.58>
Time	Datetime	23 Jan 2019 11:08 – current time	23 Jan 2019 11:08
AQI	Integer	[0, +Inf]	102
Pollutant type	String	Predefined set of pollutants	CO_2
Pollutant value	Double	[0; +Inf]	51.04
User ID	String	Predefined set of strings	Alice, Bob
Age	Integer	[0,120]	78
Pollutant sensitivity level	Pair<String, String>	Pair <[Predefined set of pollutants], [Neutral, Low, Moderate, High, Extremely high]>	<CO_2, High>
Colour blindness	Boolean	True, False	True

Defining the necessary context attributes and their value ranges for the model enables us to consider all possible situations that user can experience. The next section describes the situation reasoning of the proposed model.

3.2 Situation Reasoning

The previous section presented a detailed description of the context attributes to be used for the system's context modelling with the Context Space Theory (CST). As it was discussed in the literature review, the CST uses Situation Spaces for real life situation representations. Context State is the input data used for the reasoning. The context state is a collection of all relevant context attribute values at a certain time.

In order to obtain context attributes such as user's age, pollutant sensitivity level to pollutants and colour vision impairments a simple set of questions is developed. The full list of questions attached at the appendices section. As it was mentioned in the previous chapter, carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), particulate matter ($PM_{2.5}$) and sulphur dioxide (SO_2) are the main air pollutants. Different studies found that older adults, children and people with lung diseases are sensitive to all five pollutants, while people with heart diseases tend to be also sensitive to $PM_{2.5}$ and CO. Moreover, active people of all ages who exercise or work outdoors are more sensitive to O_3. Since sensitive groups to SO_2 and NO_2 are similar, therefore, we consider only one of them. Moreover, due to similarity of sensitive groups to CO and $PM_{2.5}$ we consider only one of them. In summary, three pollutants are selected such as NO_2, O_3 and $PM_{2.5}$ [120].3 A set of 20 questions based on a number of research studies introduced in [121]–[128]. The set contains wide variety of questions related to social status, age, lifestyle and habits of a user. Questions have multiple answers. The answers have weighted value from 0 to 4 which relates to the sensitivity levels for each pollutant such as *neutral, low, moderate, high* and *extremely high* and further used to identify sensitivity level. Weights are assigned according to the relevancy of a question to a pollutant and severity of its effects. For example, if question is “Do you have asthma?” and for answer “yes” NO_2 sensitivity weight is 4. If question is “How often do you work outdoors?” then O_3 sensitivity weight can be 3 if answer is “frequently” and 1 if answer is “rare”.

After getting responses, weights for each pollutant are collected into arrays. Then number of weights are counted. If there is at least one answer with sensitivity weight 4, then sensitivity level is defined as extremely high. Because, usually weight 4 is assigned to answers which confirm that user has a lung or heart diseases and they are extremely sensitive to pollutants. Next, if there are more than three answers with weight 3 then sensitivity level is again extremely high and in case if this number is between zero and three then the level is considered to be high and so on. Algorithm I presents the full version of the algorithm to define sensitivity level to each pollutant.

Algorithm I: Pollutant sensitivity levels calculation

INPUT: *responses* to the set of questions, pollutant *pollutantSensitivityWeight*: sensitivity weights of each answer (0,1,2,3,4), pollutantType: pollutant types (NO_2, O_3, $PM_{2.5}$)

OUTPUT: pollutant sensitivity level (neutral, low, moderate, high, extremely high)

PARAMETERS: *WeightsArray*: pollutant sensitivity weights array

METHOD:

```
for each element of responses do {
   for each pollutantType do
      push pollutantSensitivityWeight to WeightsArray }
for each element of WeightsArray do {
   for each pollutantSensitivityWeight do
      count number of pollutantSensitivityWeight; }
for each pollutantType do{
   if (number of pollutantSensitivityWeight (4) > 0) {return extremely high;}
   else {
     if(number of pollutantSensitivityWeight (3) > 3) { return extremely high; }
      else if (0 < number of pollutantSensitivityWeight (3) <= 3) { return high; }
      else{
         if(number of pollutantSensitivityWeight (2) > 5) { return high; }
         else if ( 0< number of pollutantSensitivityWeight (2) <= 5) { return moderate; }
         else {
            if(number of pollutantSensitivityWeight (1) > 7) { return moderate; }
            else if ( 0< number of pollutantSensitivityWeight (1) <= 7) { return low; }
            else { return neutral; }}}}}
```

Algorithm I. Pollutant sensitivity levels calculation.

However, the identified sensitivity levels are used as a proof of concept and cannot be utilized as a reference to relate to actual sensitivity of a person to a pollutant.

After defining the sensitivity levels, the sensitivity level to each pollutant is considered to define user's current situation.

The situation spaces defined for this thesis are based on the levels of health concern presented in [88], depending on the values of AQI. However, several changes are made due to the introduction of additional context attributes. In this research, we defined following five situation spaces to represent current ambient air quality conditions:

1. **Good Air Quality**

Air pollution has a little or no health risk and air quality is considered satisfactory.

2. **Unhealthy Air Quality**

This situation implies that a person can experience gentle health effects and respiratory irritations.

3. **Very Unhealthy Air Quality**

In this situation users can experience more serious health effects. Problems with breathing may occur and users can feel high levels of discomfort.

4. **Hazardous Air Quality**

This situation implies severe air pollution conditions and emergency conditions. Users can experience serious health effects.

5. **Very Hazardous Air Quality**

This situation is specific for users with high and extremely high pollutant sensitivity levels, meaning that effects can lead to death if not immediate rescue from the place.

Algorithms II illustrates situation reasoning algorithm based on Australian air quality index standards. In the similar manner, situation reasoning for European and US AQI standards are developed.

Algorithm II: Current situation reasoning based on Australian AQI

INPUT: pollutant AQI indices, user's pollutant sensitivity levels, pollutant types

OUTPUT: overall current situation

PARAMETERS: pollutant specific situation variable

METHOD:

```
for each pollutantType do {
   if (AQIIndex <= 33)  { pollutantSpecificSituation = good; }
   else if (33 < AQIIndex <= 66) {
      if (sensitivityLevel=="neutral") { pollutantSpecificSituation = good; }
      else { pollutantSpecificSituation = unhealthy; }}
   else if (66 < AQIIndex <= 99) {
      if (sensitivityLevel == ("neutral" || "low"))   { pollutantSpecificSituation = unhealthy; }
      else if (sensitivityLevel ==("moderate" || "high")) { pollutantSpecificSituation = veryUnhealthy; }
      else pollutantSpecificSituation = hazardous; }
   else if (99 < AQIIndex <= 149){
      if (sensitivityLevel = "high") { pollutantSpecificSituation = hazardous; }
      else if (sensitivityLevel=="extremelyHigh") { pollutantSpecificSituation = veryHazardous; }
      else { pollutantSpecificSituation = veryUnhealthy; }}
   else {
      if (sensitivityLevel == ("high" || "extremelyHigh")) { pollutantSpecificSituation = veryHazardous; }
      else { pollutantSpecificSituation = hazardous; }}}
```

Algorithm II. Current situation reasoning based on Australian AQI.

Table 10 illustrates all possible situation spaces that can take place depending on the final pollutant sensitivity for normal and sensitive groups and overall AQI indices taking into account all relevant pollutant types. For example, if AQI value is between 201 and 300 and user's pollutant sensitivity level is neutral, then user's current situation is *very unhealthy*. The same values of AQI for the high sensitivity level makes the situation *hazardous*, while for extremely high sensitivity level, the situation is *very hazardous*.

Table 10. Situation Spaces of the proposed model.

Australian AQI range	European AQI range	User's pollutant sensitivity level / US AQI	Neutral	Low	Moderate	High	Extremely high
0-33	Good	0-50	Good	Good	Good	Good	Good
34-66	Fair	51-150	Good	Unhealthy	Unhealthy	Unhealthy	Unhealthy
67-99	Moderate	151-200	Unhealthy	Unhealthy	Very Unhealthy	Very Unhealthy	Hazardous
100-149	Poor	201-300	Very Unhealthy	Very Unhealthy	Very Unhealthy	Hazardous	Very Hazardous
>150	Very Poor	301-500	Hazardous	Hazardous	Hazardous	Very Hazardous	Very Hazardous

For users without any colour vision impairments, green to red gradient colours are used to represent from good to hazardous situations, while black colour refers to very hazardous situation. Table 11 presents the colours for normal vision given at the first column.

Table 11. Colour schema for CAVisAP data visualization.

	normal vision colours	colour blind vision colours	Deuteranopia	Protanopia	Tritanopia	Monochromacy
Good	#00FF00	#FEE5D9				
Unhealthy	#FEFF00	#FB6A4A				
Very Unhealthy	#FF7F00	#DE2D26				
Hazardous	#FF0000	#A50F15				
Very Hazardous	#000	#000				

However, if the user has any type of colour deficiency, we use colours at the second column of the Table 11, which can be distinguished by people with different colour impairments. In addition, the table gives an illustration on how these colours are perceived by people with different types of colour blindness such as deuteranopia, protanopia, tritanopia and monochromacy. Colours for blindness safe visualization are chosen using a tool called *ColorBrewer* [129]. Information on how people with colour vision impairments see the selected colours are obtained via *Sim Daltonism* [130] simulation tool.

3.3 Summary

This chapter presented a CST-based model for outdoor air pollution visualization. Firstly, we define context attributes of the system. Then value types and ranges of each context attribute were defined. We presented pollutant sensitivity level calculation algorithm. Following this, we define situation spaces which represent real-life situations according to the context attributes values. The next current situation reasoning algorithm was presented. Following this we presented context-aware data visualization scheme which considers on colour vision impairments of users. The next step of the research is to implement the context aware system for outdoor air pollution visualization.

4 SYSTEM ARCHITECTURE AND IMPLEMENTATION

This chapter of the thesis illustrates the proposed system architecture. In addition, internal and external system components are illustrated. Moreover, the chapter demonstrates context acquisition and situation reasoning algorithms as well as implementation of data acquisition and storage and data visualization layers.

4.1 System Architecture and Components

This section presents the description of the system architecture and system's components. The system comprises of four layers such as Data Acquisition, Data Collection and Storage, Data Processing and Data Visualization. Figure 11 illustrates interaction between the layers.

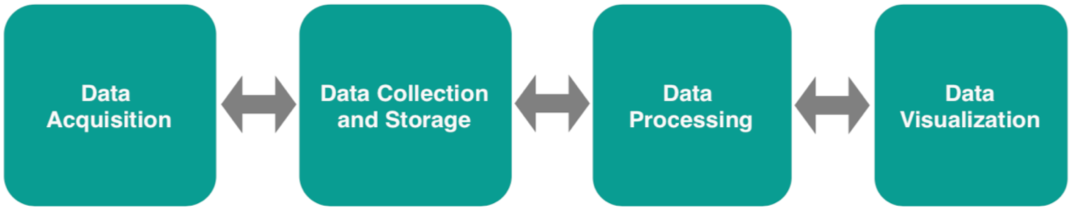


Figure 11. The CAVisAP layered system architecture.

The data acquisition layer is responsible for outdoor air pollution data collection from sensing devices and external data sources. The data collection and storage layer provides a service for aggregation and storage of historic data. Data processing layer is responsible for context information retrieval, situation reasoning, and data sharing. Finally, data visualization layer provides a user interface and up-to-date visualization of air pollution data. Figure 12 shows the overall architecture of the system with details on tools and software used during development process.

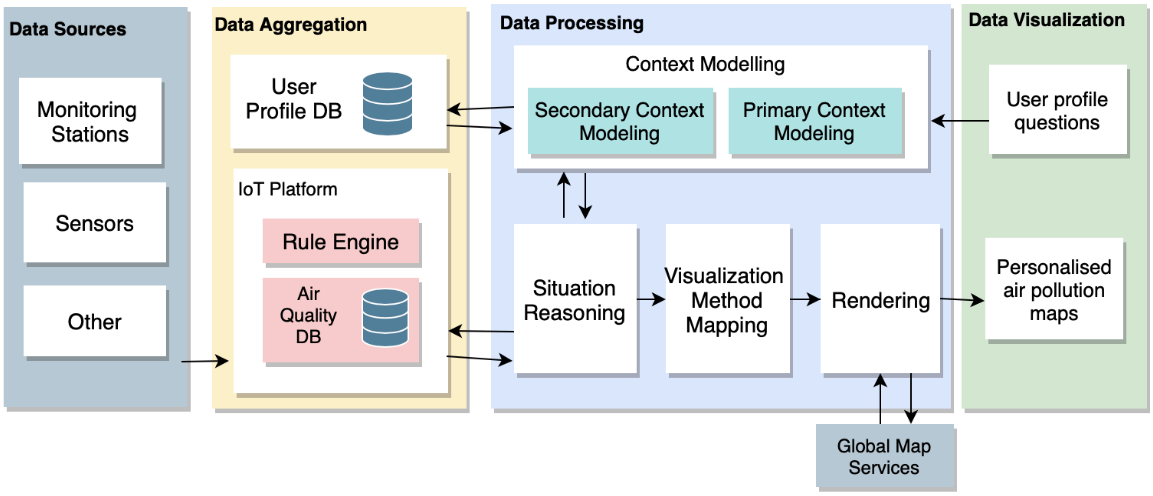


Figure 12. System Architecture and Components.

The following sections provide comprehensive description on implementation of each layer of the system.

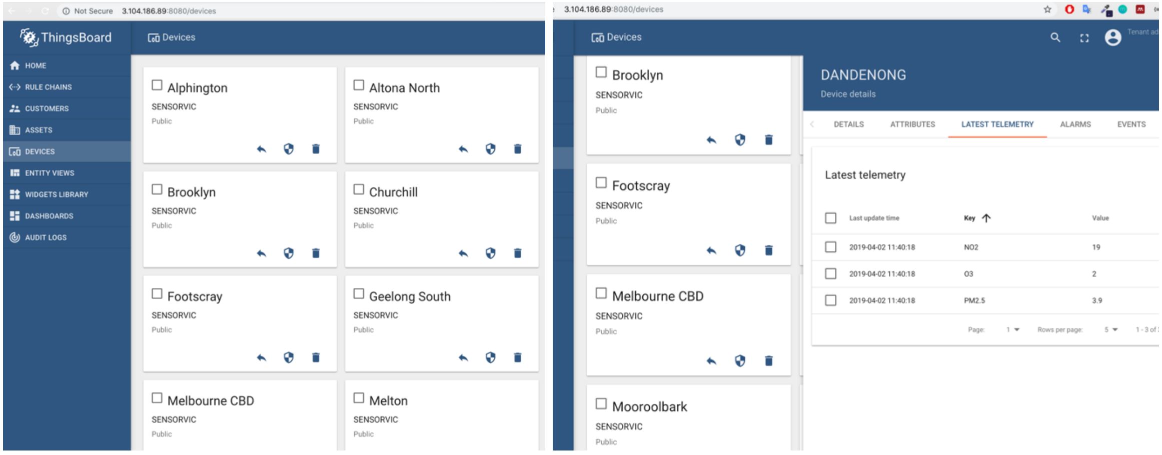
4.2 Data Acquisition and Storage

Location is one of the primary contexts of any context-aware system. Therefore, as a proof of concept this system was developed for two different regions such as Australia and Europe. Data for Australian air pollution was obtained from web service provided by the Environment Protection Authority of Victoria [131]. The agency provides open access to air quality measurements for all operating sites in the Victoria state. The APIs provide information on the hourly readings as well as historical data for a range of pollutants such as CO, O_3, NO_2, SO_2, $PM_{2.5}$ and PM_{10}. Data for Europe is obtained from open-source project OpenAQ [132]. In addition, sensor data provided by Lulea University of Technology (LTU) is used for a use case scenario in the Skelleftea city, Sweden.

The next, all data collected from the above-mentioned sources is ingested into the open-source IoT platform called ThingsBoard. The platform allows to process incoming data with rule chains based on message content or entity attributes [133].

We installed open source edition of ThingsBoard IoT platform into an Amazon Web Services (AWS) [134] Elastic Cloud Computing instance provided by LTU. In the ThingsBoard platform we created virtual devices representing actual stations. Each device adopts attributes such as name, latitude and longitude from a real-world air pollution monitoring station. Moreover, air pollution data obtained from stations is ingested to the respective virtual device.

Figure 13 illustrates an example of virtual devices created for Melbourne city, Australia.



(a) (b)

Figure 13. Screenshots from ThingsBoard: a) Virtual sensors; b) Latest telemetry data.

ThingsBoard provides APIs for server-side applications to control devices. The platform supports protocols such as MQTT, CoAP, and HTTP which are standard IoT protocols. In order to bind data streams from the real-world stations to the virtual devices we used MQTT protocol.

The platform supports various database options such as SQL, NoSQL and hybrid database and provides possibility to select the storage for main entities and where to store timeseries data. In our implementation, SQL database is used to store both main entities and timeseries data. After obtaining data from aforementioned sources and storing them in the IoT platform we need to process it and get value from the raw data. The next section describes implementation of the data processing layer.

4.3 Data Processing

Data processing layer comprises of two parts. First, defining user profile in order to further define user context. Second, situation reasoning based on user context and timeseries data streaming from IoT platform. Data processing layer is implemented in Node.js, which is an open source development platform for executing JavaScript code server-side [135].

Figure 14 illustrates an example of a question, answers and pollutant specific weights for answers from the set.

```
8: {
    q: "How often do you do physical exercises?",
    a: ["I do not exercise", "Less than once a week", "1-2 times a week", "3-5 times a week", "More than 5 times a week", "I do not know/Not sure"],
    no2SensitivityWeight: [0,0,0,1,2,0],
    o3SensitivityWeight: [0,0,0,1,2,0],
    pm25SensitivityWeight: [3,2,1,0,0,0]
},
```

Figure 14. Example question to define pollutant sensitivity levels.

For example, we consider a set of 20 questions and count NO_2 sensitivity weights. There might be seven answers with weight 0, four answers with weight 1, seven answers with weight 2, two answers with weight 3 and zero answers with weight 4. Then according to the algorithm, the sensitivity level to NO_2 is defined as high since there are more than five answers with weight 2. After defining the sensitivity levels, user is asked to answer a true/false question on colour blindness. This is needed to further provide colour-blind safe data visualization. Lastly, user is asked to give an access to current location after which profile is saved with unique id. Figure 15 illustrates an example of user's profile information.

```
▾object
  userId: "id-f7wthwwn5vj"
  no2sensitivity: "neutral"
  o3sensitivity: "high"
  pm25sensitivity: "high"
  colorBlindness: "true"
▾currentLocation: object
    lat: -37.8472505
    lng: 145.1145886
```

Figure 15. Example of user profile information.

Defining user profile enables us to further provide context-aware air pollution data visualization. Especially if we consider the case when the same air quality levels can be safe for one person and might be vitally dangerous for another. Moreover, visualizing air pollution levels with colours visible for people with normal vision might not give any value to colour-blind person. Therefore, being aware of user context makes it possible to provide critically valuable information to users in a comprehensive for them way.

The next step is to identify user's current situation with regards to the air pollution levels in the nearby places. Users are provided with choice to change proximity radius to see air pollution in their current location. After getting the proximity radius, query is made to the IoT platform to get locations of the devices. Figure 16 illustrates SQL command which is used to filter the devices within proximity radius.

```
SELECT id,
       ( 3959 * Acos  (Cos  (Radians(78.3232)) * Cos(Radians(lat)) *
                                       Cos(Radians(lng) - Radians(65.3234)) + Sin
                      (
                                   Radians(78.3232)) * Sin(Radians(lat))) ) AS
       distance
FROM   devices
HAVING distance < 30
ORDER  BY distance
LIMIT  0, 20;
```

Figure 16. Query to find devices in a proximity radius.

After getting the nearby device details, we query ThingsBoard for the latest telemetry data from each of the stations. Then AQI for each pollutant is calculated depending on the region where user is located currently. Next, we calculate user's current situation taking into account their sensitivity to each pollutant and respective pollutant AQI value. As it was introduced in the previous thesis chapter, we use Algorithm II to reason user situation.

4.4 Data Visualization

To provide context-aware visualization, the first user profile needs to be obtained. Users are given an opportunity to select their pollutant sensitivity levels when registering to the system. For this purpose, login and registration interfaces are developed. In addition to the simple registration form where users can select from dropdown menu sensitivity levels (neutral, low, moderate, high and extremely high), we provide a link to the set of questions that can help users to define their sensitivity to NO_2, O_3, and $PM_{2.5}$. Further users are transferred into the main interface of the system which contains a personalized air pollution map in the current location of the user. The map uses different colours to provide the same level of pollution for users with different sensitivity levels as defined in the context model. Moreover, the set of colours differs for colour-blind and users with normal vision. A number of techniques are used to visualize air pollution levels such as heat maps, coloured air pollution spots maps, pinpoints and pinpoints with indices. The data processing layer and data visualization layer are implemented in NodeRED [136]. NodeRED is a flow-based development tool for visual programming. The NodeRED allows interconnecting physical input/output, databases, cloud-based systems, and API's. The Node-RED is based on flow-based programming and the flows are managed by the different type of "nodes", where each node has a well-defined function; the node receives data, then processes the data, and then it passes that data on to the next node in the flow or completes the data processing. The tool is implemented in JavaScript and the majority of nodes have pre-built configuration, which requires minimum programming skills. However, specific nodes provide an interface to write scripts for more complex solutions. Figure 17 shows a screenshot of workflow in NodeRED.

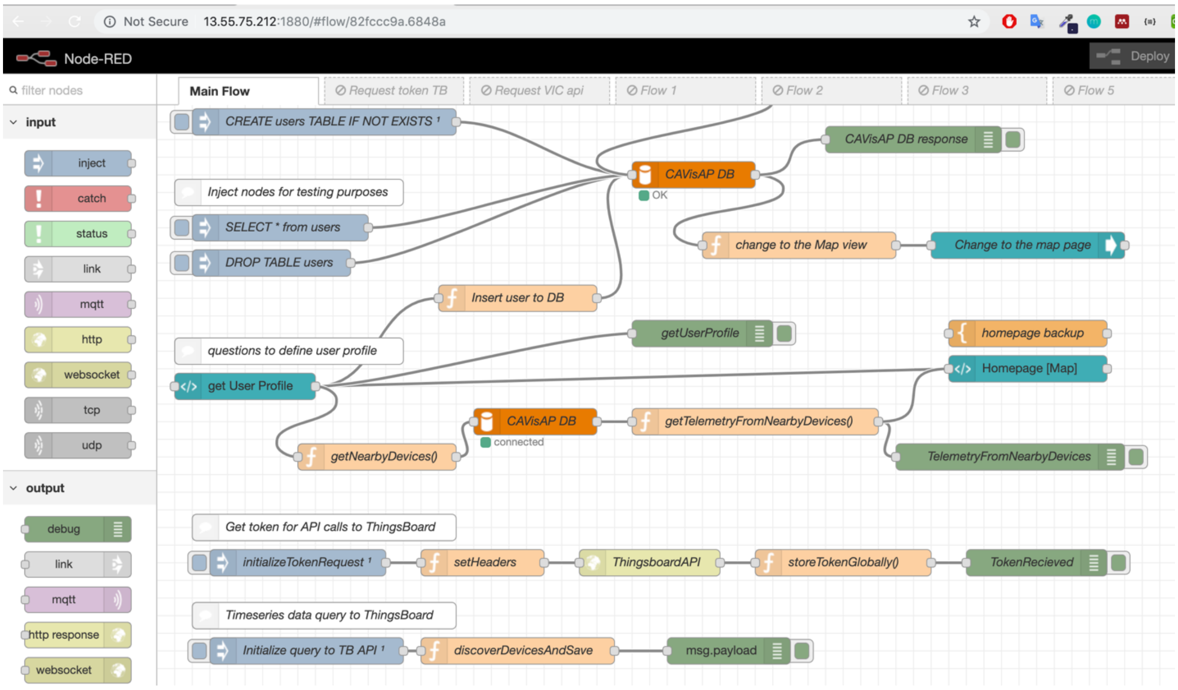


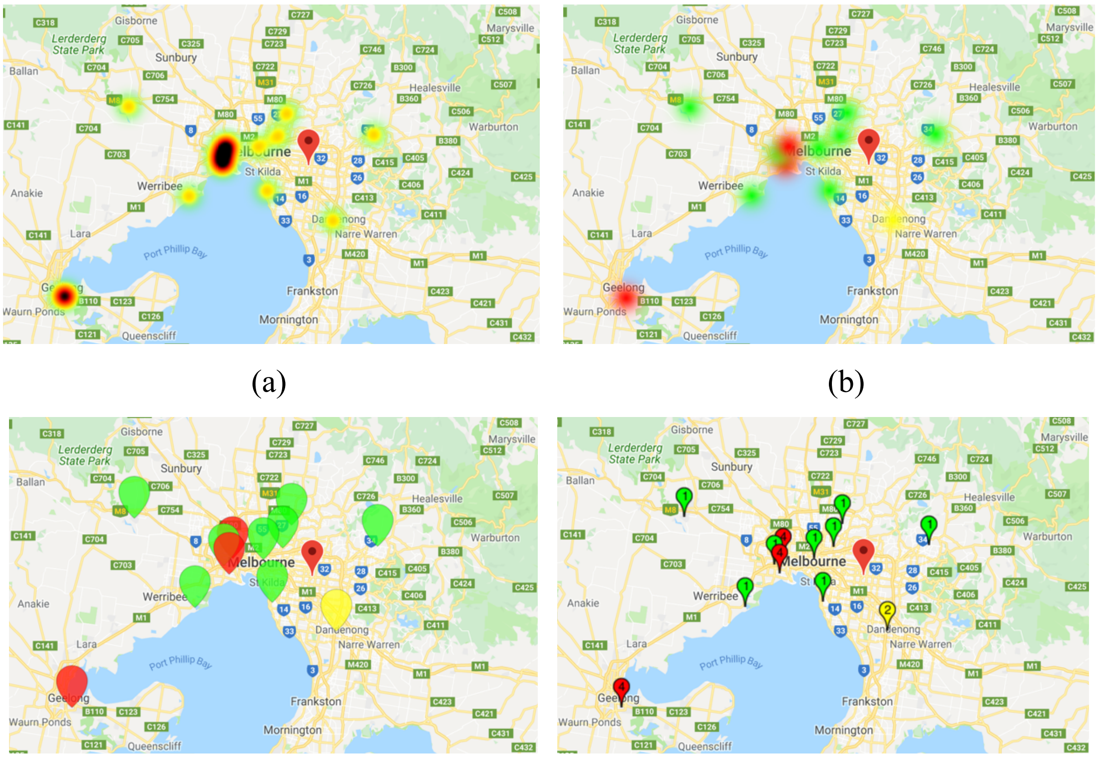
Figure 17. NodeRED workflow.

To provide context-aware visualization, the first user profile needs to be obtained. Users are given an opportunity to select their pollutant sensitivity levels when registering to the system. For this purpose, login and registration interfaces are developed. In addition to the simple registration form where users can select from dropdown menu sensitivity levels (neutral, low, moderate, high and extremely high), we provide a link to the set of questions that can help users to define their sensitivity to NO_2, O_3, and $PM_{2.5}$. Further users are transferred into the main interface of the system which contains a personalized air pollution map in the current location of the user. The map uses different colours to provide the same level of pollution for users with different sensitivity levels as defined in the context model. Moreover, the set of colours differs for colour-blind and users with normal vision. A number of techniques are used to visualize air pollution levels such as heat maps, coloured air pollution spots maps, pinpoints and pinpoints with indices. The interfaces of the system are implemented using dashboard nodes in NodeRED which enable the extension of pre-build interface functionality. We use Google Maps JavaScript API for places, routes and locations [15]. The Maps JavaScript API allows to customize maps with additional content and imagery for display on web pages and mobile devices and features. Figure 18 illustrates an initial callback function *initMap()* called by Google Maps API which creates the *Map* object. After creating the initial map object, we call *showInitialHeatmap()* function, which adds *heatmap* layer for air quality data obtained from IoT platform.

```
function initMap() {
    var markerArray = [];
    var directionsService = new google.maps.DirectionsService;
    var directionsDisplay = new google.maps.DirectionsRenderer;
    var stepDisplay = new google.maps.InfoWindow;
    var currentLocation = {lat: userLat, lng: userLng};
    map = new google.maps.Map(document.getElementById('map'), {
      zoom: 15,
      mapTypeControl: false,
      center: {lat: userLat, lng: userLng}
    });
    directionsDisplay.setMap(map);
    showInitialHeatmap();
  }
```

Figure 18. Initialization of map object.

In addition to heatmaps, we provide a number of visualization methods such as coloured air pollution maps, pinpoints and pinpoints with indices which helps users personalize their experience. Figure 19 shows different visualization techniques applied for the same data.

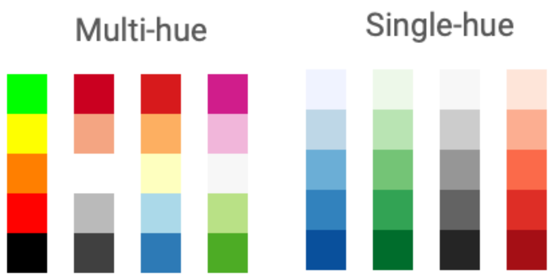


(a) (b)

(c) (d)

Figure 19. Different visualization methods applied for the same dataset: a) heat map; b) pollution spots map; c) pinpoints; d) pinpoints with indices.

According to the values user context on colour blindness we provide different set of colour hues for pollution visualization. Figure 20 shows an example of multi-hue colours which are provided for users with normal vision and single-hue colours which are colour-blind safe.



(a) (b)

Figure 20. Set of colour hues used for visualization: a) multi-hue; b) single-hue.

After implementing the air pollution visualization of current location, we implemented the functionality which provides users with context-aware pollution-safe routes planning. First, we receive origin and destination as an input from the front-end, then call Google Maps

Routes API to get all alternative routes. After getting the route alternatives, we query ThingsBoard to receive information for all the devices in the proximity radius. Further, we find nearby stations to each route. Figure 21 shows the distance calculation function according to geographical coordinates.

```
function getLatLngDistance(lat1,lon1,lat2,lon2) {
  var R = 6371; // for km
  var dLat = (lat2-lat1) * Math.PI / 180;
  var dLon = (lon2-lon1) * Math.PI / 180;
  var a = Math.sin(dLat/2) * Math.sin(dLat/2) +
          Math.cos(lat1 * Math.PI / 180 ) * Math.cos(lat2 * Math.PI / 180 ) *
          Math.sin(dLon/2) * Math.sin(dLon/2);
  var c = 2 * Math.atan2(Math.sqrt(a), Math.sqrt(1-a));
  var d = R * c;
  return Math.round(d*1000);
}
```

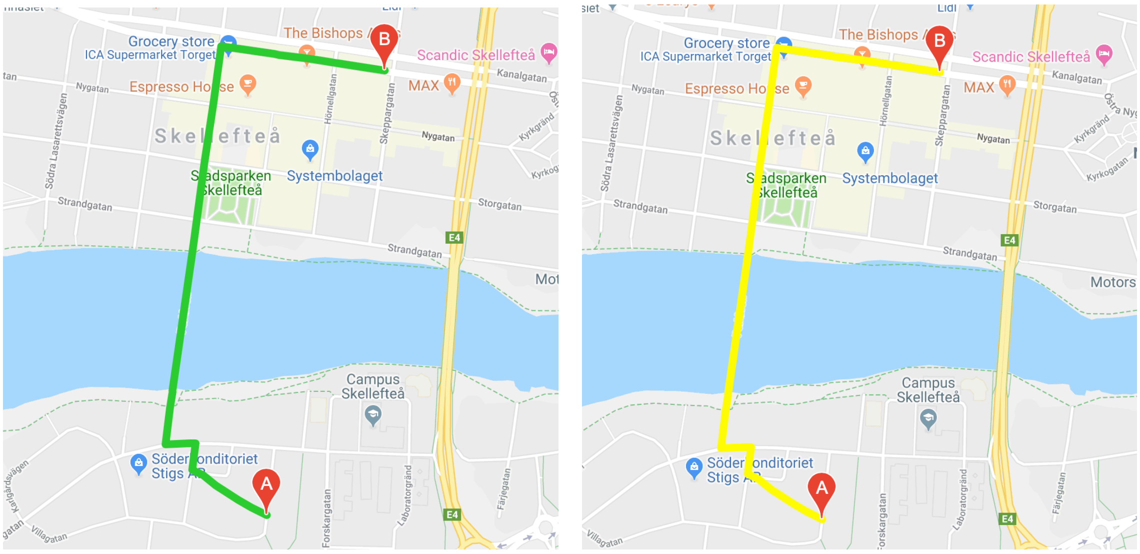
Figure 21. Function to calculate distance between coordinates.

After getting the list of stations along each route alternative, we reason situation according to user context at each station. The overall situation of the route is equated to the situation of the station with the highest air pollution rate. Further, we compare situations on all route alternatives and get the index of the safest route. According to the situation at the chosen route, we get the visualization colour. Further, we call Google Maps directions rendered function by passing safest route index and route colour. Figure 22 shows the code snippet of visualizing the safest route.

```
var getSafestRouteIndex = Object.keys(routeAndSituationMap).reduce((a, b) =>
                          routeAndSituationMap[a] < routeAndSituationMap[b] ? a : b);
var getSafestRouteSituation = routeAndSituationMap[getSafestRouteIndex];
var getRouteColor = getCurrentSituationColor(getSafestRouteSituation);
directionsDisplay.setDirections(response);
  directionsDisplay.setRouteIndex(parseInt(getSafestRouteIndex));
  directionsDisplay.setOptions({
    polylineOptions: {
      strokeColor: getRouteColor,
      strokeWeight: 7
    }
  });
```

Figure 22. Pollution-safe route visualization implementation.

Figure 23 presents how visualization changes for users with different levels of pollutant sensitivity despite the same levels of pollution.



(a) (b)

Figure 23. Visualization of context-aware route planning: a) for healthy person; b) for pollutant-sensitive person.

The next chapter present experiments and results to validate our context-aware visualization model and system implementation.

4.5 Summary

This chapter presented CAVisAP architecture which aims to provide context-aware visualization of outdoor air pollution maps and routes. The architecture consists of four layers: data acquisition, data aggregation, data processing and data visualization. Further, the chapter illustrated implementation of each layers of the system, technologies and tools used. Main source of data was public APIs provided by municipalities in Melbourne and Skelleftea cities. For data aggregation and storage ThingsBoard IoT platform was used. The data processing layer was implemented in Node.js. The data visualization was developed in NodeRED IoT wiring tool with integration of Google Maps API. The next section present experiments held and review the obtained results as well as discuss sustainability value of the proposed system.

5 EXPERIMENTS, RESULTS AND DISCUSSION

This chapter presents different testing scenarios of CAVisAP system and discusses obtained results. Moreover, it presents sustainability analysis of the system from individual, social, environmental, financial and technical perspectives.

5.1 Experiments and Results

In order to evaluate the developed system, we simulate different users' profiles with different sensitivity levels. Moreover, since the real-life data streams obtained for Victoria and Skelleftea show relatively good levels of air pollution, we create extra virtual devices with generated data. These devices are used to test the system for severe air pollution levels. In the first set of experiments, we test the difference in visualization of the same AQI for users with different sensitivity levels. We create five user profiles with different sensitivity levels to $PM_{2.5}$ and neutral sensitivity to NO_2 and O_3. Table 12 illustrates the user profiles.

Table 12. Pollutant sensitivity levels of users.

Users	Sensitivity levels		
	NO_2 sensitivity	O_3 sensitivity	$PM_{2.5}$ sensitivity
Alice	neutral	neutral	neutral
Bob	neutral	neutral	low
John	neutral	neutral	moderate
Jack	neutral	neutral	high
Rita	neutral	neutral	extremely high

In the first experiment we consider five stations with good to very hazardous AQI levels. Table 13 shows the details on station names and respective $PM_{2.5}$ and AQI values at each station.

Table 13. AQI values at each station.

Stations	Address	$PM_{2.5}$ value	AQI
st_1	Woolworths Burwood	10.2	25.5
st_2	Lundgren Reserve	14.9	37.25
st_3	St Scholastica	30.9	77.25
st_4	Hawthorn Art Centre	45.8	114.5
st_5	Unity of Melbourne	67.5	168.75

Figure 24 shows locations of the stations on the map and situation at each node for a user with neutral sensitivity for all pollutants. Table 14 presents situation reasoning for all five users calculated with aforementioned algorithm.

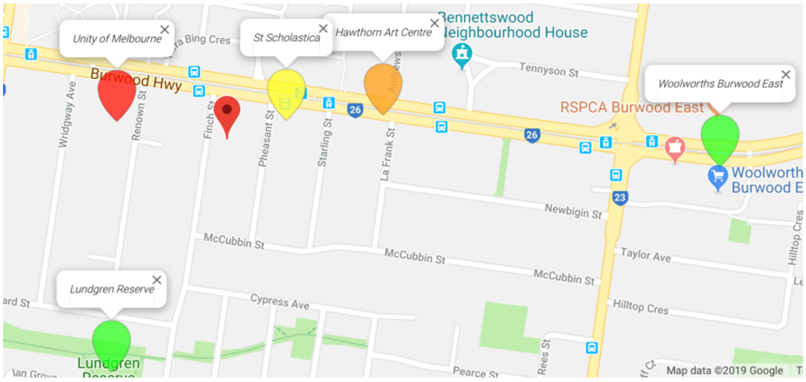


Figure 24. Location of the stations in the first experiment.

Table 14. Situation Reasoning at each station.

Users	Stations				
	st_1	st_2	st_3	st_4	st_5
Alice	good	good	unhealthy	very unhealthy	hazardous
Bob	good	unhealthy	unhealthy	very unhealthy	hazardous
John	good	unhealthy	very unhealthy	very unhealthy	hazardous
Jack	good	unhealthy	very unhealthy	hazardous	very hazardous
Rita	good	unhealthy	hazardous	very hazardous	very hazardous

Figure 25 presents visualization of the air pollution data for the first set of experiments. As it can be seen, situation at Woolworth Burwood remains good for all five users, while at

Lundgren Reserve its unhealthy for all users which have at least low level of sensitivity to $PM_{2.5}$. Moreover, situation at St Scholastica changes from unhealthy to hazardous and at Hawthorn Art Centre from very unhealthy to very hazardous depending on the users' pollutant sensitivity levels.

a) b) c)

c) d)

Figure 25. Visualization of the same air pollution data for users with different sensitivity levels: a) neutral; b) low; c) moderate; d) high e) extremely high

At the second experiment we consider only one user, Alan with different sensitivity levels to all three pollutants, NO_2, O_3 and $PM_{2.5}$. Table 15 presents the user profile.

Table 15. Sensitivity to NO_2, O_3 and $PM_{2.5}$.

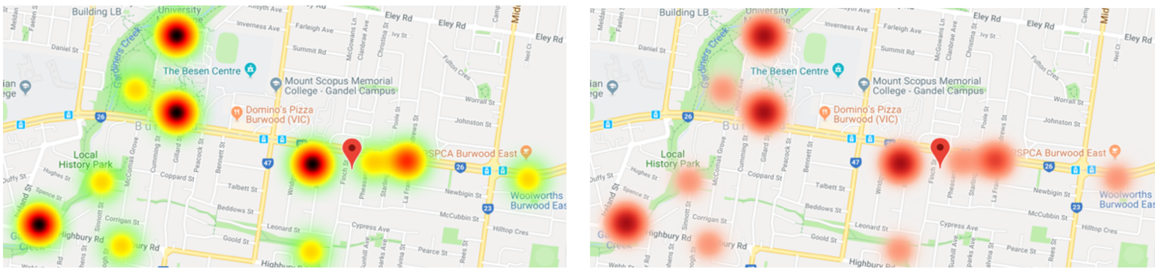
Users	Sensitivity levels		
	NO_2 sensitivity	*O_3 sensitivity*	*$PM_{2.5}$ sensitivity*
Alan	neutral	moderate	Extremely high

At the second scenario, we consider five stations with different situations depending on pollutant type. For example, at the station Unity of Melbourne station air quality is good regarding NO_2 and O_3 values. However, the level of particulate matter is very hazardous. Hence, overall situation of Alan is very hazardous. Moreover, at Deakin Burwood Co. user's situation is unhealthy with regards to particulate matter but there is very unhealthy ozone level for moderate sensitivity groups. Therefore, situation of Alan is very unhealthy at the node. Table 16 provides full information on pollutant measurements at each of the stations and pollutant-specific situation and overall situation of Alan at each station.

Table 16. Air quality at each station.

Stations	Deakin Uni.	Benn. Reserve	Deakin Burwood Co.	The Settlers Shelter	Unity of Melbourne
NO_2 value	45	39.5	84.9	82.7	0.7
NO_2 situation	good	good	unhealthy	unhealthy	Good
O_3 value	25.6	12.1	78.9	78.3	0.6
O_3 situation	good	good	very unhealthy	very unhealthy	good
$PM_{2.5}$ value	11.8	24.1	10.8	35.1	67.5
$PM_{2.5}$ situation	good	unhealthy	unhealthy	hazardous	very hazardous
Overall situation	good	unhealthy	very unhealthy	hazardous	very hazardous

Further, we test the CAVisAP to differentiate visualization depending on the users' colour vision impairments in order to provide meaningful information in a readable form. Figure 26 illustrates the change of colour scheme for colour-blind users.



a) b)

Figure 26. Visualization colour schemes: a) default; b) colour-blind safe.

The next experiment is to test air pollution-based route planning. In this experiment we simulate three user profiles Alice, Bob and Jack who has different sensitivity levels to NO_2 and $PM_{2.5}$. Table 17 illustrates the sensitivity levels of users.

Table 17. Simulated user profiles for pollution-safe route suggestions experiment.

	NO_2 sensitivity	$PM_{2.5}$ sensitivity
Alice	0	4
Bob	1	4
Jack	4	1

Alice, Bob and Jack want to bike from Villagatan 32 to Kanalgatan 46B in Skelleftea city. Figure 27 illustrates route alternatives from the origin to destination suggested by Google Maps.

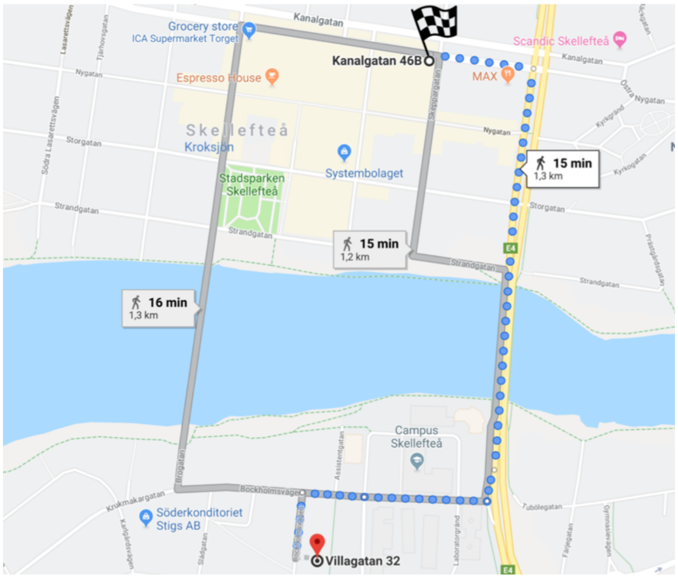


Figure 27. Route alternatives from origin to destination.

We have created 7 virtual stations in ThingsBoard for Skelleftea city. Two of the virtual stations stream real-life data for the provided by LTU. However, the air pollution levels in Skelleftea are good and are not enough to test our system for reasoning the severe air pollution situations. Therefore, we have used simulated air pollution data for the remaining 5 stations. Table 18 illustrates the station names and air pollution data at each station. The stations which stream real-life data have [Live] tag.

Table 18. Air quality at each station.

	NO_2 value	NO_2 AQI	$PM_{2.5}$ value	$PM_{2.5}$ AQI
Brogatan	86	Fair	12.5	Fair
Skellefteå Bryggeri	45	Good	15	Fair
Data Ductus [Live]	0.2	Good	0.33	Good
ICA Supermarket	0.4	Good	0.6	Good
LTU Leif's office [Live]	0.03	Good	0	Good
MAX	125	Moderate	27	Moderate
Skelleftea Nygatan	0	Good	22.7	Moderate

To get overall situation at each route alternative for each user, we have considered air pollution monitoring stations within 70m proximity distance along the route**.** Table 19 presents the distance of stations from each route alternative.

Table 19. Distance of stations from the route alternatives.

	Route A	Route B	Route C
Brogatan	16m		
Skellefteå Bryggeri		35m	
Data Ductus	20m		
ICA Supermarket	27m		
LTU Leif's office		66m	66m
MAX			49m
Skelleftea Nygatan		25m	

There are three stations along the route A, two along the route B, one along the route C and one is close to both routes B and C. The next we reason situation at each route alternative according to the user context. Overall air quality of the route is equal to the data of the station with the highest pollution rate. From the received air quality values and distance of the stations, we obtain that Route A has fair levels of NO_2 and $PM_{2.5}$. Route B has good levels of NO_2 and moderate levels of $PM_{2.5}$. The route C has moderate levels of both pollutants. Table 20 presents overall air quality status at each of the routes.

Table 20. Situations along the route alternatives.

	NO2	PM2.5
Route A	fair	fair
Route B	good	moderate
Route C	moderate	moderate

Getting the air quality information along each route enables us to validate system's situation reasoning. As it was illustrated before the same levels of air quality might affect differently users with different sensitivity levels. Table 21 presents situation reasoning at each route alternative for each of the users.

Table 21. Situation reasoning at each route alternative.

		Alice	Bob	Jack
Route A	NO_2-based situation	Good	Unhealthy	Unhealthy
	$PM_{2.5}$ -based situation	Good	Good	Good
	Overall situation	**Good**	**Unhealthy**	**Unhealthy**
Route B	NO_2-based situation	Good	Good	Good
	$PM_{2.5}$ -based situation	Hazardous	Hazardous	Unhealthy
	Overall situation	**Hazardous**	**Hazardous**	**Unhealthy**
Route C	NO_2-based situation	Unhealthy	Unhealthy	Hazardous
	$PM_{2.5}$ -based situation	Hazardous	Hazardous	Unhealthy
	Overall situation	**Hazardous**	**Hazardous**	**Hazardous**

Alice is highly sensitive to $PM_{2.5}$ but she is tolerant to NO_2. Routes B and C show high levels of particulate matter pollution. Route A has unhealthy levels of NO_2. Since she is tolerant to NO_2, for Alice situation at the route A remains good, therefore, biking via route A is the safest option. Figure 28a shows the context-aware route planning visualization for Alice.

Bob also has high sensitivity to $PM_{2.5}$. As for Alice, situations at the routes B and C are hazardous for him. However, in contrast, with Alice, Bob has low sensitivity to NO_2. Therefore, situation at the route A is unhealthy for Bob. Since, the other routes are hazardous, route A is the safest option for Bob. CAVisAP suggests the same route for Bob and Alice, however, they are provided with different colours for visualization depending on their context. Figure 28b presents context-aware route suggestions visualization for Bob.

Jack is extremely sensitive to NO_2. Therefore, route A is not safe for him. Moreover, he has low sensitivity to $PM_{2.5}$. Therefore, his situation at the route B and C is unhealthy. Since, the route C is longer than route B, the system suggests Jack to take route B. Figure 28c context-aware route suggestion visualization for Jack.

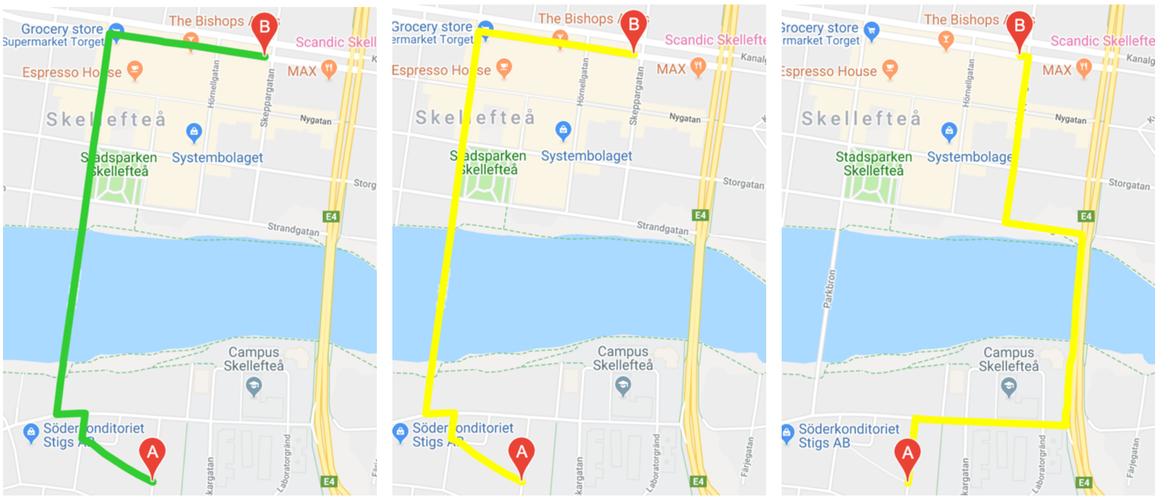


Figure 28. Context-aware pollution-safe route suggestions for: a) Alice; b) Bob; c) Jack.

The experiments show how adopting user context can change reasoning of air quality. Personalization of air pollution-based route planning provided users with an ability to choose the safest route.

5.2 Sustainability Analysis

Creating awareness on air pollution can contribute to both reducing exposure and decreasing emission levels. Moreover, the air quality information is required by scientists, regional and national planners and policy-makers to support them in taking savvy decisions on managing and controlling the environment. Air quality monitoring provides necessary scientific basis for developing policies, setting objectives and planning enforcement actions [5]. We have reviewed different air pollution related studies which could support our system's sustainability contribution.

A study in [137] found that in the absence of a toll during the national holidays in China, the amount of vehicles on the road exceeded the socially optimal number and outdoor air pollution escalated by about 20%, while the amount of particulate matter rise by 26%. Authors in [138] present a survey of major stakeholders involved in environmental policy development in Scotland and found that the invisibility of the problem both in health and economic terms cause the lack of progress in reducing air pollution. The study concludes that to tackle this challenge real-time air pollution and its health impact information must be widely available. Another research held in Beijing in 2018 illustrates the influence of air pollution on cycling behaviour of citizens. The authors found that during highly polluted days the number of cyclists significantly decline, and people tend to switch to other travel modes. Since cycling is a well-established eco-friendly mode of transportation, the study provides an evidence that sustainable transportation requires environmental protection and healthy air conditions for open-air travel [139]. Moreover, findings in [140] show that visualization interfaces, located in public spaces can contribute to social awareness increase and lead to sustainable behaviour change of citizens as well as can influence meaningful participation of citizens to locally relevant topics.

The study in [141] presents qualitative analysis of the role of visualization techniques used to create and distribute information on the process of public policymaking. The study findings show that the visualization tools and methods used to create a visual information increases transparency and significantly influences policy. Figure 29 present the conceptual framework of how data visualization could affect the policy-making process.

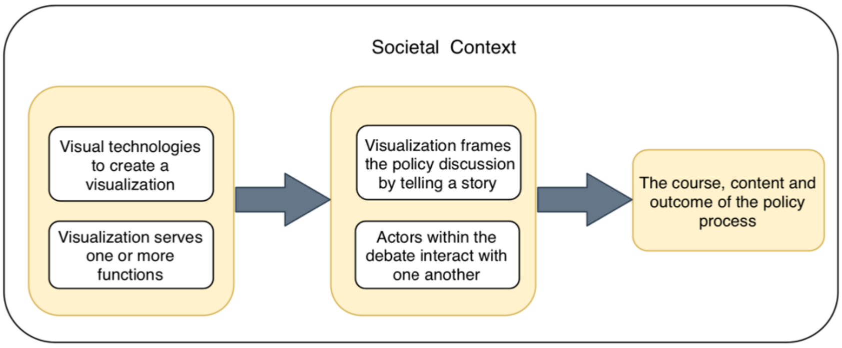


Figure 29. Conceptual framework of influence of data visualization on policy-making.

Researchers in [142] present a “data compact,” – a communication model for scientists and policymakers that could support the translation of environmental monitoring data into knowledge that can be used for policy-making illustrated in Figure 30. The study presents two use cases of data compact where scientific data is used to control ozone exhausting substances and the potential reasons for the disconnected utilization of major scientific research reports in managing corrosive precipitation antecedents.

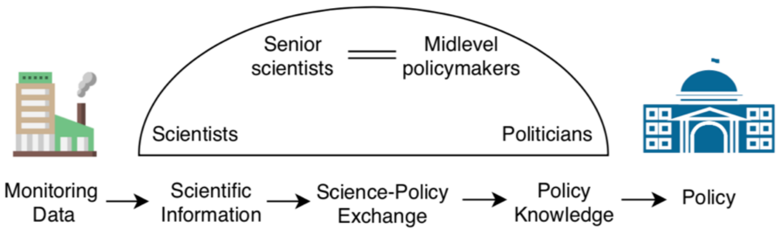


Figure 30. Data compact. [142]

Taking into account analysis of the role of air pollution monitoring and visualization, we present a five-dimensional sustainability analysis of CAVisAP system according to the framework presented in [143][144]. Figure 31 illustrates the sustainability analysis pentagon.

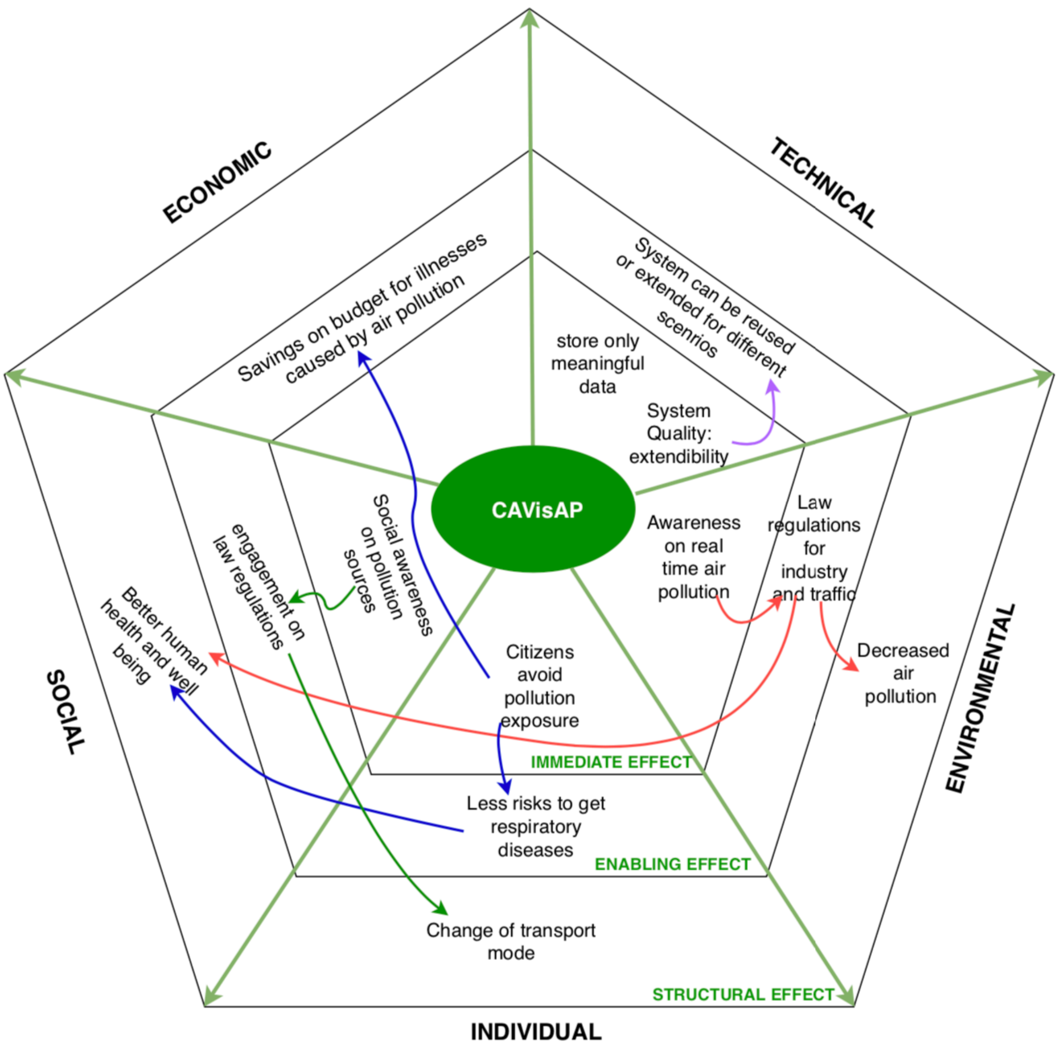


Figure 31. CAVisAP five-dimensional sustainability analysis.

Table 22 contains full version of sustainability analysis and presents immediate, enabling and structural effects of CAVisAP in five dimensions such as social, individual, environmental, economic and technical.

Table 22. Immediate, enabling and structural effects of CAVisAP

	Immediate effect	Enabling effect	Structural effect
Social	• Social awareness on polluted areas	• Social awareness on effects of pollution • Engagement on air quality regulations	• Better social health and well-being • Decrease social health inequality • Clean air for society • Subsidies for eco-friendly vehicle acquisition
Individual	• Individuals avoid pollution exposure • Individuals are informed of pollution sources	• Less risks to get respiratory diseases • Increased knowledge on pollution causes • Engagement to local air quality regulations	• Informed change of transport mode • Green mindset establishment
Environmental	• Need for mitigation of pollution sources	• Change of traffic-related policies • Restrictions for industrial pollution	• Less emissions, less pollution • Promotion of eco-friendly transport modes • Increased funding for environmental activities
Economic	• Less expenses on pollution caused health issues	• Increased demand on eco-friendly transportation • Increased demand on pollution monitoring devices and services	• Subsidies for eco-friendly vehicle production • Investments on pavements for walkers and bikers • Increased pollution related taxes
Technical	• Compute and store only meaningful information	• Less storage, less processing time	• Less hardware usage

The framework enables to analyse our system's immediate, enabling and structural effects in individual, social, environmental, economic and technical aspect. Since the major focus of our system is providing personalized air pollution maps and route-planning, CAVisAP enables citizens to avoid polluted areas, which helps them to reduce pollution-related health risks. This means users avoid possible health related expenses. Further, awareness on environmental problems enable individuals and society to engage to policy-making process and demand governments to take actions against environmental pollution. Moreover, with an equipped knowledge on pollution causes, citizens might reconsider their choice of transport and shift to environment-friendly cars, public transport or bike. Visualization of invisible problem such as air pollution enables policy-makers to enact and enforce the international, national and local air quality regulations. Moreover, governments might promote environment-friendly transport modes and provide subsidies to individuals and businesses to produce and utilize the eco-vehicles. From the technical aspect the CAVisAP adopts context-aware computing approach, which enables to store and process only meaningful information. Consequently, decreases the demand for hardware usage. The pentagon in Figure 31 provides detailed connection between first, second and third order effects of our proposed system.

6 CONCLUSIONS AND FUTURE RESEARCH

This chapter concludes the research findings and discusses future investigation directions.

6.1 Conclusions

This research aimed to propose, develop, implement and validate a real-time context-aware visualization system using the widely used IoT paradigm applied for outdoor air pollution use case. To achieve the aim, we first reviewed state-of-the-art literature in the areas of IoT, context-aware computing, data visualization and air pollution monitoring. After defining the research gaps on context-aware visualization of air pollution maps we developed a CST-based model. The proposed model consists of algorithms to define pollution sensitivity, context-aware situation reasoning and pollution-safe route planning. The four layered system architecture comprising of data acquisition, data aggregation, data processing and visualization layers was presented. Further, we present an implementation of the context-aware system CAVisAP for personalized outdoor air pollution visualization and route planning was presented. The system provides context-aware visualization of three air pollutants such as nitrogen dioxide (NO_2), ozone (O_3) and particulate matter ($PM_{2.5}$) in the city of Melbourne, Australia and Skelleftea, Sweden. In addition to primary context as location and time, CAVisAP takes into account users' pollutant sensitivity levels and colour vision impairments to provide personalized pollution maps. Moreover, the system provides users with pollution-safe route planning. The developed system was tested for a set of scenarios considering variety of user profiles with different pollutant sensitivity levels. A set of questions was developed to identify users' sensitivity levels to NO_2, O_3 and $PM_{2.5}$. The experiments justify the importance of considering user profile, since the same level of air pollution is proven to be very hazardous for one user while another can feel only a little discomfort. Moreover, CAVisAP attempt to provide a novel approach to visualize air pollution data considering users' colour vision impairments. This is critically important, since misinterpreting of air pollution colours can lead to uncompromising health issues. The sustainability analysis of the system was conducted and first, second, third order effects were discussed. Since the major focus of our system is providing personalized air pollution maps and route-planning, CAVisAP enables citizens to avoid polluted areas, which helps them to reduce pollution-related health risks. This means users avoid possible health related expenses. Further, awareness on environmental problems enable individuals and society to engage to policy-making process and demand governments to take actions against environmental pollution. Moreover, with an equipped knowledge on pollution causes, citizens might reconsider their choice of transport and shift to environment-friendly cars, public transport or bike. Visualization of invisible problem such as air pollution enables policy-makers to enact and enforce the international, national and local air quality regulations. Moreover, governments might promote environment-friendly transport modes and provide subsidies to individuals and businesses to produce and utilize the eco-vehicles. From the technical aspect the CAVisAP adopts context-aware computing approach, which enables to store and process only meaningful information. Consequently, decreases the demand for hardware usage.

6.2 Future Research Directions

This research findings can be extended in numerous ways. The first, the system could incorporate context-aware prediction to enable users to plan their future trips and avoid possible pollution exposure. Moreover, the system performance and efficiency can be compared with existing solutions for pollution-based route planning proposals. The system can be enhanced with considering additional context attributes which could affect visualization method choice such as device profile and network connectivity. Lastly, user experience tests can be conducted to identify the most suitable visualization methods. Long-term qualitative studies can be conducted to identify behaviour change of users which are provided with pollution-based route alternatives.

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APPENDIX A. A set of questions to personalize air pollution visualization and pollutant-specific weights of answers.

```
AQ_QUESTIONS = {
        1: {
          q: "How do you commute to work?",
          a: ["By own car", "By public transport", "By bike", "By walk", "None of the options"],
          no2Index: [0,1,2,2,0],
          o3Index: [0,1,2,2,0],
          pm25Index: [0,1,2,2,0]
        },
        2: {
            q: "Is your age between 18 and 65?",
            a: ["yes", "no"],
          no2Index: [0,3],
          o3Index: [0,3],
          pm25Index: [0,3]
        },
        3: {
            q: "Which proportion of your working/studying hours do you spend outdoors?",
            a: ["More than 75%", "Between 50% to 75%", "Less than 50%", "I do not work/study", "I do not know/Not sure"],
          no2Index: [0,0,0,0,0],
          o3Index: [3,2,1,0,0],
          pm25Index: [0,0,0,0,0]
        },
        4: {
            q: "Which proportion of your working/studying hours do you spend in sitting position?",
```

```
        a: ["More than 75%", "Between 50% to 75%", "Less than 50%", "I do not work/study", "I do not know/Not sure"],
        no2Index: [2,1,0,0,0],
        o3Index: [2,1,0,0,0],
        pm25Index: [3,2,1,0,0]
    },
    5: {
        q: "How often do you do physical exercises?",
        a: ["I do not exercise", "Less than once a week", "1-2 times a week", "3-5 times a week", "More than 5 times a week", "I do not know/Not sure"],
        no2Index: [0,0,0,1,2,0],
        o3Index: [0,0,0,1,2,0],
        pm25Index: [3,2,1,0,0,0]
    },
    6: {
        q: "How often do you eat fast food?",
        a: ["I do not eat fast food", "Less than once a week", "1-2 times a week", "3-5 times a week", "More than 5 times a week", "I do not know/Not sure"],
        no2Index: [0,0,0,1,2,0],
        o3Index: [0,0,0,1,2,0],
        pm25Index: [0,0,1,2,3,0]
    },
    7: {
        q: "How often do you smoke?",
        a: ["I do not smoke", "Less than once a day", "1-2 times a day", "3-5 times a day", "More than 5 times a day", "I do not know/Not sure"],
        no2Index: [0,0,1,2,3,0],
        o3Index: [0,0,1,2,3,0],
        pm25Index: [0,0,0,0,0,0]
    },
    8: {
        q: "Does anyone in your family smoke?",
```

```
        a: ["Yes, I live with a smoking person", "No, I live with non-smokers", "I do not know/Not sure"],
        no2Index: [2,0,0],
        o3Index: [2,0,0],
        pm25Index: [0,0,0]
    },
    9: {
        q: "How often do you consume alcohol drinks?",
        a: ["I do not drink alcohol", "Less than once a week", "1-2 times a week", "3-5 times a week", "More than 5 times a week", "I do not know/Not sure"],
        no2Index: [0,0,1,2,3,0],
        o3Index: [0,0,1,2,3,0],
        pm25Index: [0,0,1,2,3,0]
    },
    10: {
        q: "How would you assess your health conditions in terms of breathlessness?",
        a: ["No breathlessness except with strenuous exercise", "Short of breath when hurrying or walking up a slight hill", "Walk slower on flat ground than friends/have to stop for breath when walking at your own pace", "Stop for breath after walking for a few minutes on the flat", "Breathless when dressing/undressing or too breathless to leave the house sometimes", "Breathless when sitting still"],
        no2Index: [0,1,2,3,4,4],
        o3Index: [0,1,2,3,4,4],
        pm25Index: [0,1,2,3,4,4]
    },
    11: {
        q: "Does anyone in your family have lung diseases?",
        a: ["My parent(s)", "My sibling(s)", "My spouse", "My child(ren)", "No", "I do not know/Not sure"],
        no2Index: [1,1,1,0,0,0],
        o3Index: [1,1,1,0,0,0],
```

```
        pm25Index: [0,0,0,0,0,0]
    },
    12: {
        q: "Does anyone in your family have heart diseases?",
        a: ["My parent(s)", "My sibling(s)", "My spouse", "My child(ren)", "No", "I do not know/Not sure"],
        no2Index: [0,0,0,0,0,0],
        o3Index: [0,0,0,0,0,0],
        pm25Index: [1,1,1,0,0,0]
    },
    13: {
        q: "The LAST time you had your blood pressure checked, was it normal or high?",
        a: ["High", "Normal", "I do not know/Not sure"],
        no2Index: [0,0,0],
        o3Index: [0,0,0],
        pm25Index: [3,0,0]
    },
    14: {
        q: "The LAST time you had your cholesterol checked, was it normal or high?",
        a: ["High", "Normal", "I do not know/Not sure"],
        no2Index: [0,0,0],
        o3Index: [0,0,0],
        pm25Index: [3,0,0]
    },
    15: {
        q: "Do you have asthma?",
        a: ["Yes", "No", "I do not know/Not sure"],
        no2Index: [4,0,0],
        o3Index: [4,0,0],
        pm25Index: [4,0,0]
```

```
},
16: {
    q: "Do you have allergy to pollen?",
    a: ["Yes", "No", "I do not know/Not sure"],
  no2Index: [3,0,0],
  o3Index: [3,0,0],
  pm25Index: [3,0,0]
},
17: {
    q: "Do you have diabetes?",
    a: ["Yes", "No", "I do not know/Not sure"],
  no2Index: [0,0,0],
  o3Index: [0,0,0],
  pm25Index: [3,0,0]
},
18: {
    q: "Are you aware of any heart diseases (hypertension, coronary artery disease, etc.) you have?",
    a: ["Yes, I am aware. And I have heart diseases", "Yes, I am aware. And I do not have any heart diseases", "I do not know/Not sure"],
  no2Index: [0,0,0],
  o3Index: [0,0,0],
  pm25Index: [4,0,0]
},
19: {
    q: "Are you aware of any lung diseases (chronic bronchitis, emphysema, chronic obstructive pulmonary disease, etc.) you have?",
    a: ["Yes, I am aware. And I have lung diseases", "Yes, I am aware. And I do not have any lung diseases", "I do not know/Not sure"],
  no2Index: [4,0,0],
  o3Index: [4,0,0],
  pm25Index: [4,0,0]
```

```
    },
    20: {
        q: "If you are female, are you pregnant?",
        a: ["Yes", "No", "I am not female"],
      no2Index: [3,0,0],
      o3Index: [3,0,0],
      pm25Index: [3,0,0]
    }
};
```