Low cost Air Quality Sensor Network for Aalborg City

A pilot deployment and research project using wireless sensors and IoT

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Joint European Master in Environmental Studies
Cities and Sustainability
Master Thesis
School of Architecture, Design and Planning

AALBORG UNIVERSITY

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This report is accompanied by an informational poster which will be exhibited at the dissertation examination on June 18th in the Create building part of Aalborg University campus.

Preface

The hereby presented master thesis is developed and submitted as a requirement for the completion of the Joint European Master's program in Environmental Studies Cities and Sustainability - JEMES CiSu. The timeline established for the fulfilment of this thesis comprehend the time frame from February to the first week of June, 2018.

With today's world heading to an ever evolving technological innovation, cities have the chance to add real time metrics to their doings. Air quality has proven to be one of the heaviest indicators for the analysis of quality of life in recent publications. This, along with the other different dimensions seen in an urban setting, could be assessed with its corresponding interrelations aiming to a better and certainly more efficient decision making. Technology's role as a potential ally when pursuing smart sustainable development relays the importance of this research. The author considers vital to challenge technology through research to path its evolution accordingly to real life challenges and requirements. This wouldn't be optimal if not obtaining technologies maximum potential and efficiency. The present work involves the analysis of the implementation from location selection to potential usages after installation. The usage of metrics on environmental and related categories indicators are also proposed along with the data value chain from this first deployment in the city of Aalborg.

The deployment of this pilot aims to set the baseline of an array of sensors in the future. Therefore, it is foreseen that this pilot low cost air quality monitoring sensor network enables future research and continues evolution due to the versatility as the core nature of its deployment.

Reading guide

Sources references and citations are under the American Psychological association 6th edition style and are listed in alphabetical order at the end of this document. References from books, academic articles and published work will be cited as (Author/Organization, Year). However, some may appear as (Author, n.d.) due to the unspecified year on the given source.

Declaration of Authorship

I, hereby, declare that the following Master Thesis is an original work and that the outcomes are a representation of my own research. The research has not been previously submitted, in part or as a whole, to this or any other university. All information derived from work done by others has been acknowledged and accurate cited, to the best of my knowledge, in the text and the list of references.

Diana Carolina Moreno Saltos
June 8th, 2018
Aalborg, Denmark

Acknowledgment

I would like to acknowledge the contribution of this thesis to supervisor Martin Lehman. Professor Lehmann acted as the medium between Aalborg Municipality and Aalborg University and thus, facilitator of all needed actions for the deployment of the sensor network. His guidance and knowledge shared throughout the process is well appreciated.

The co-supervision by Professor Célia Alves supported technically the outcomes of this research. Professor Celia as air quality expert provided knowledge on the feasibility of the potentials of air quality data. Her support and passionate input directed me to the final outcome of this project.

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I would also like to thank the interviewed people for this research for their important insights. Likewise, the physical deployment of the network of sensors required infrastructure that was successfully set by Anders Otte. I express my very great appreciation to him.

Lastly, my very special gratitude to all my colleagues, their constant work, dedication and thoughtfulness enriched my professional and personal being. After a JEMES CiSu experience, friends become family, and for my family from the journey, a piece of our souls is now to be spread out in the world, accompanying us anywhere our paths lead each of our futures.

To my family, friends, and country which are fundamental pieces of my very existence. To whom and which I belong and dedicate all achievements, efforts and commitments.

"Stay hungry, stay foolish, stay curious, […]"

- Tom Hiddleston

Acronyms/ Abbreviations

LCAQSN	Low cost air quality sensor network
AQ	Air quality
IDE	Integrated development environment
API	Application programming interface
EPA	Environmental Protection Agency of the United States of America
WHO	World Health Organization
DCE	Danish Centre for Environment and Energy
OGC	Open Geospatial Consortium
ISO	International Organization for Standardization

Abstract

Smart cities worldwide currently use wireless technology and Internet of Things platform in order to widen their monitoring, assessment and analysis of environmental parameters such as air quality. Agglomerated urban areas have proven to be the most contaminated ones, posing a major threat for human direct exposure. This work has the intention to deploy a low cost air quality monitoring sensor network as a pilot program for a medium sized city. Air quality metrics, data strategy, methodologies and opportunities for future works are identified. The main research question proposed is the following: How can the implementation of a low cost air quality monitoring sensor network deliver value to the city of Aalborg? Low cost AQ sensors were allocated and distributed accordingly to the city context in the urban background of the city of Aalborg. Literature review is proposed to emphasize the importance of accountability on air quality pollution along with proposed similar initiatives in other cities. Document analysis is used to gain information about the instruments and the potentials of the metrics of its measurements. Geographical analysis and observations are conducted for the correspondent allocation of the instruments throughout the city. All these, complemented with interviews related with similar projects. At last, the air quality sensor network was deployed through the utilization of strategically installed gaseous pollutant wireless sensors. The work concludes with the deployment of the pilot along with the first experiences of its implementation. Additionally, further usage of the air quality data obtained from the wireless sensor network is proposed.

Key words

Air quality, Wireless sensor network, IoT, Environmental monitoring, Smart cities

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1. Introduction

Demographia© defines urban areas as a continuously built up land mass of urban development that is within a labour market and does not contain rural land (Demographia, 2017). A built-up urban, urbanized or urban agglomeration area is also used to refer to an urban area. Pollutants are defined as any substance present in ambient air and likely to have harmful effects on human health and/or environment as a whole. Where ambient is an outdoor air in the troposphere excluding working places (EU, 2008).

The Clean Air Act of the United States Environmental Protection Agency set six common air pollutants identified as harmful not only for human health and the environment but also for the infrastructure heritage of a city since chemical reactions can contribute to material deterioration (US EPA, 2017). According to the WHO, 4.2 million deaths are attributed to ambient air pollution (WHO, 2018a). Therefore, the importance on the monitoring of environmental parameters such as air pollution is emphasized.

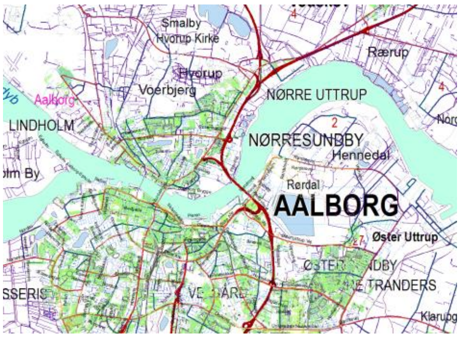
This project follows up a third semester project labelled "Cities, Big data & IoT" which pointed out the opportunities and evolution of Big Data, the Internet of Things (IoT) in the context of an urban environment. Nowadays, cities are not only needed to employ digitalization, technology, internet of things and big data but its interoperability is what would really define the smartization of a city.

Unequivocally, the "smart" concept has gained popularity in the public management field since the deployment of affordable portable devices and the coming of new means of wireless communication such as the internet. This trend grew to the extent on becoming the most prominent sector for IT services in the near future. By following technology evolution, cities see a clear opportunity and have the potential of reshaping the way complex systems such as urban areas are analysed, at a level that was not possible before. Data obtained by smart devices when visualized in a geospatial format facilitates the understanding of systems that may or may not have been visible to be analysed before. This matter is exponentially enhanced when integrating multidimensional data, coming from different sources, layer out to schematize the complex system of a city.

Aalborg is characterized by a high level of entrepreneurship and local solutions and home of Aalborg University which makes the city perfect for these kinds of developments. The city is engaged to provide better citizenship, utilization of scarce resources, create sustainable community solutions and establishing new production activities (O. B. Jensen, 2014). The city recognized this opportunity and decided to join a number of cities worldwide who are joining efforts to tackle tomorrow's challenges. Under the Horizon 2020 framework, the city decided to create Smart Aalborg as a project to join the Smart City Network in Denmark (Aalborg Kommune, 2014). The city of Aalborg defines the Smart Aalborg as an initiative supporting both sustainability and technological development within the municipality. With the hand of technology, the municipality plans to minimize society's limited resources for the benefit of the three pillars of sustainability. The project aims to focus its efforts in buildings, citizens, infrastructure, mobility and supply (Aalborg Komunne, n.d.). Additional further insights on smart city current projects of the municipality are not available online.

Aalborg is Denmark's third largest municipality with 205,000 inhabitants. Urban areas in the municipality have approximately 125,000 inhabitants, classified as a medium-sized urban area (Aalborg Kommune, 2018; Organisation for Economic Co-Operation and Development, 2016). The following table describes the urban Aalborg layout:

Figure 1 - Layout of Aalborg city



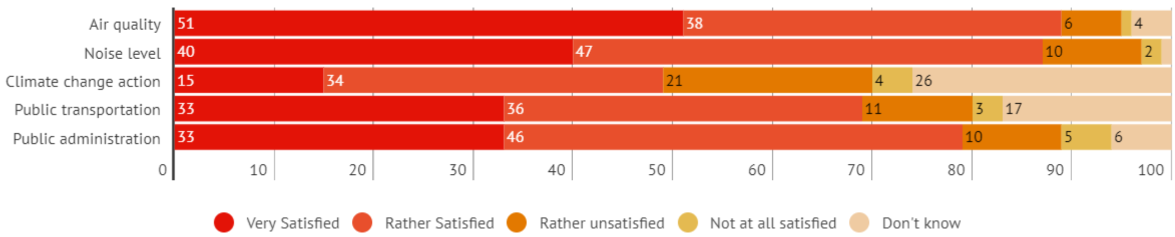
Source: (Erhvervsstyrelsen, 2018; ESRI, 2016; Google Maps, 2018; OIS, 2018; Open Data DK, 2015; Styrelsen for Dataforsyning og Effektivisering, 2018)

Aalborg is considered as an environmental city leader after its involvement with the creation of the "Aalborg charter" in 1994 and the last "Aalborg Commitments" in 2004. The Aalborg charter states the awareness of the people affected by environmental problems such as air pollution along with the acknowledgement of necessary pollution prevention measures at the source (Charter of European Cities & Towns Towards Sustainability, 1994). The Aalborg Commitments commits cities to take responsibility to protect, preserve, and ensure equitable access to natural common goods, compromising efforts to improve AQ while reducing the impact of transportation on the environment and public health (European Local Governments, 2004). Concerning Key Performance Indicators for Sustainable Development, Denmark is an official member of the International Organization for Standardization (ISO).

Recent reports on air quality both regionally and locally have presented data on air quality and pollution concentrations that doesn't surpass limit values (Ellermann et al., 2017b; European Environment Agency, 2017). Regardless, information regarding premature deaths attributable to Particulate matter ($PM_{2.5}$), Ozone (O_3), and Nitrogen dioxide (NO_2) reveal important numbers related to those concentrations. In 2014, Europe – 41 countries – in total registered 428000, 78000 and 14400 premature deaths due to the previously stated pollutants accordingly. Denmark alone registered 3 470, 130 and 110 for premature deaths attributed to $PM_{2.5}$, O_3, and NO_2, respectively. As seen, Particulate matter is shown to be the major threat to human health.

In 2016, the European Commission's "Perception of Quality of Life in European Cities" was published. In it, indicators were used to survey people regarding their satisfaction with their city in relation with the environment, barely over a half of the surveyed sample showed a high satisfaction with the city's AQ. Overall, Aalborg, scored high with 98% of the sample indicating high satisfaction with the city they develop their lives in. From there the fact that Aalborg is in the top four happiest cities to live in Europe (European Commission, 2016). When specific parameters about the environment and the public services management are evaluated though, contrast is depicted in the picture below.

Figure 2 - Aalborg indicators for Quality of Life



Source: (European Commission, 2016; Infogram, 2018)

Now, even though this survey is subjective by nature to the questions asked of the public it is still a viable source of information that could denote lack of accountability and participation of the public on the parameter of AQ. This research aims to analyze and propose the possibilities of a LCAQMSN and therefore its potentials to help citizens obtain a higher quality of life.

The Danish Centre for Environment and Energy (DCE) is in charge of the Danish Air Quality Monitoring Programme which provides insights on air pollution and furthermore its potential impact on the environment. Official stationary stations are feeding the database in Copenhagen, Odense, Aarhus, Aalborg and some rural areas but real time data is only provided by automatic sensors which are not the majority. In Aalborg, two stations are considered in the program, regardless one of them is temporarily closed due to construction and is to be relocated in the future (Department of Environmental Sciences, 2018; Ellermann et al., 2017a).

The complexity of air pollution is known by its fluctuation on a very local scale – hyper locally. Wind, as any other fluid in nature, acts as air pollution main driver in its transportation. Besides, atmospheric, chemical, meteorological, or even physical infrastructure can increase or decrease concentrations constantly. The affordability of low cost environmental sensors promises to enable hyper locally AQ monitoring citywide throughout its deployment. On one hand, the latter could represent a more efficient environmental monitoring system of AQ and on the other, ubiquitous real-time data the possibility for stakeholders – academia, citizens, industry and municipality - to make use of the data in order to support their performances and decision making. Furthermore, low cost AQ sensors have been catalogued as promising in an urban setting plagued with a set of challenges ahead that emphasize the importance of field research and test technology on the way.

As for now, the importance of urban air pollution and the importance of its monitoring along with the smart city concept have been introduced along with the introduction to Aalborg's AQ current monitoring setting. This project aims to introduce the first steps of low cost AQ monitoring sensors as the tools that enable monitoring and make the Smart City possible and attainable. This accountability of smart projects is necessary since the process is indeed on-going and there is always room for the system's improvement at any level. The data obtained from this pilot AQ sensor network could represent the universal language in which AQ parameters can be translated acquiring a synergistic effect in the city system. By developing the pilot, this research has the intention to identify related stakeholders in order to seek alliances and collaboration with future smart projects and to challenge technology through research.

There are two research sub-questions that will navigate through the development of this master thesis. These are: i) What are the potentials/opportunities of the real-time urban air quality data? ii) What strategy urban air quality data should have aiming to support decision making at the multiple city management levels? These questions will set the baseline for the main research question set as: How can the implementation of a low cost air quality monitoring sensor network deliver value to the city of Aalborg?

A variety of methodologies have been proposed for the development of this research; literature review, observations, interviews and document analysis. *Literature review* was conducted to comprehend the importance and state-of-the-art of urban AQ monitoring along with its opportunities with regards to technology and sensing networks. The same approach was made in order to create an understanding on how to assess the Smart Aalborg project and the city readiness for subsequently smart projects under the three components of sustainability. *Document analysis* regarding Key Performance Indicators related to outdoor urban air pollution is included in order to analyse the relevant parameters that a LCAQMSN could provide. *Geospatial analysis* is performed with the relevant geo-information provided. *Interviews* with the experts developing similar projects and associates working for the Aalborg Municipality are planned. *Observations* and site visits for Aalborg citywide are performed in order to analyse the most relevant points for the sensors to be allocated, followed right after its geospatial analysis. At last, a pilot methodology for the implementation of a LCAQMSN is described for the specific case of Aalborg Municipality. For this part interviews and document analysis are performed. The methodologies used to answer each of the research questions are fully described in the methodologies section.

1.1 Project Definition

Taking into consideration the derivable of this research, the following main research question along with its sub-questions - i) and ii) - are proposed:

How can the implementation of a low cost air quality monitoring sensor network deliver value to the city of Aalborg?

i) What are the potentials/opportunities of the real-time urban air quality data?

ii) What strategy urban air quality data should have aiming to support decision making at the multiple city management levels?

The fulfilment of the following objectives along with the scope of this research will therefore answer the research question proposed.

1.2 Objectives

- Comprehend the importance of urban outdoor AQ monitoring
- Identify the state-of-the-art of urban outdoor AQ monitoring in other cities
- Define the needed metrics that can be supported by an AQ monitoring sensor network seeking a smart sustainable city
- Understand the challenges seen with the usage of low cost AQ sensors for AQ monitoring
- Identify the opportunities of urban outdoor AQ data for the city of Aalborg
- Propose an AQ data strategy structure for the deployment
- Assemble the content obtained throughout this research into a methodology for the deployment of an AQ monitoring sensor network in Aalborg
- Compute, analyse and geo-visualize the first outcomes of the deployed AQ monitoring sensor network (to be presented in the dissertation of the Master Thesis)

2. Methodology

The knowledge and support information required was identified accordingly and consequently, the methodology to obtain it. The core methodology used for this report is detailed below.

2.1 Literature Review

The present work compiles information acquired from different sources such as academic research papers, governmental and non-governmental organizations, and European and international standardization documentation. Thus, a general comprehension on how urban AQ is monitored along with new technologies is presented along with the understanding on smart sustainable cities and its assessment.

On one hand, the presentation of the importance of air pollution monitoring in an urban setting is the basic start point to further develop the research project. A state-of-the-art of new technologies and low cost AQ sensors involved in its monitoring is included in section 3.1. On the other hand, the concept of smart sustainable cities along with research on its assessment is allocated in section 3.2. Challenges while deploying these types of technologies are also addressed.

It is worth mentioning that projects listed to signalize the state-of-the-art of low cost AQ sensors were obtained from official open available sources. Also, these sources of information have their own limitations due to the way that information is disclosed by each project administration.

2.2 Document and geospatial analysis

Document analysis was carried out for the current AQ monitoring network in Denmark in order to analyse their methodology and the possible contribution the LCAQMSN can provide to it. The Libelium sensor official documentation which is a compendium of technical, programming, operational and developing guides for general advice were assiduously revised. The Libelium forum for developers was also consulted for programming advice.

Geospatial analysis is presented and the following sources were used for the acquisition of openly accessible Aalborg geo-information:

Table 1 - List of geo-information sources consulted

Institution	URL	Description
Styrelsen for Dataforsyning og Effektivisering	https://www.kortforsyningen.dk/	The Danish Board of Data Supply and Efficiency distribution of maps and geodata on the Internet[1]
Open Data DK	http://www.opendata.dk/	Data sets from different municipalities is collected and displayed in this one nationwide portal[2]
Erhvervsstyrelsen	http://kort.plandata.dk/spatialmap?	Plandata is a digital register for physical planning in Denmark, ensuring uniqueness and digitally available data sets[3]
OIS	https://ois.dk/	This Public Information Server is a state-owned database collecting information about properties in Denmark[4]

[1](Styrelsen for Dataforsyning og Effektivisering, 2018), [2](Open Data DK, 2015), [3](Erhvervsstyrelsen, 2018) and [4](OIS, 2018)

These datasets were collected in different formats such as shapefile (.shp) or Comma Separated Values (.csv) files in order to analyse and correlate geographically the data such as traffic analysis, land use, city layout, city infrastructure, etc. In this way, the locations of the sensors and the AQ data strategy were proposed. The software used for the geospatial analysis is ArcGis 10.4.

2.1 Observations in situ and Interviews

Agglomeration areas and hotspots in Aalborg were identified according with the documentation and geospatial information gathered. Here, observations and site visits took place in order to identify the environment in which sensors could be potentially allocated amongst the city. City's heavy traffic, major roads, bus routes, pedestrian agglomerations and infrastructure were also assessed for this purpose.

Two key interviews were scheduled and successfully reached as part of this methodology. For the first one, *Thomas Ellermann* - senior researcher of the Department of Environmental Sciences from Aarhus University – was reached by phone in order to get some understandings from the Danish Air Quality Monitoring in Aalborg.

For the second one, *Anders Yde-Nielsen* – student assistant at Aalborg Municipality's ITS and Traffic Planning department – was interviewed in person in order to get insights in the traffic monitoring system of Aalborg.

The mentioned methodology was reshaped constantly as the project progressed. At first, when planning the research methodology, multiple interviews and external collaboration was assigned. There was an expected collaboration from the municipality since contact and project dissemination was held previous to the starting point of this research. Aalborg Kommune department coordinator for Urban and Landscape Management and environment - traffic and roads - and Smart City Aalborg Project Managers were contacted by several means; regardless, neither interview nor collaboration was successfully performed due to a mentioned "inability to contribute with this research due to the current project situation". Neither further explanation nor contact was reached.

The input these interviews would have given to the outcome of this research is thought to be extremely important. The implementation of smart initiatives relies not only in infrastructure and interoperability but on a certain framework/guidance and leadership that is not clear how to be reached in the city of Aalborg. Despite the information found online, the inconveniences experienced by this research only reflect on the inadequate or perhaps incomplete concrete efforts and investments towards smartization of the municipality. Further, as usage of metrics is clearly supported by the literature of this research, this research aimed to build up from an existent baseline with high feasibility to be implemented. Notwithstanding, the insights on the current usage of indicators and metrics was not obtained. Most importantly, real potentials and opportunities were expected to be fulfilled through those interviews.

Interviews were also projected and contact was attempted with people involved on the city projects with LCAQMSN's mentioned in literature review as in RESCATAME and CTT2.0. Nevertheless, no hint of possible collaboration was received during the timeline of this research.

It is important to note that additionally, there was an expected collaboration from the department of computer sciences from the Aalborg University with regards on the technical architecture of the sensor network. Regardless, multiple inconveniences made it impossible to actually occur. This solely was a deciding factor that determined the actual communication protocol this pilot sensor network worked with.

The information expected to be collected through those interviews is estimated to be covered by the other methodologies detailed above.

3. Literature Review

3.1 Urban air quality monitoring importance, metrics and geo-visualization

Urban Air Quality and impacts on human health - Urban areas are also considered areas of growth and human agglomeration. This agglomeration refers, according to experts, to increase in activity within a determinate area. This growth makes an urban area of significant importance due to its numerous social, economic and environmental benefits (Trasportation Association of Canada, 2004). Yet, those same parameters are also affected by the related poor AQ urban areas are associated with. This therefore evidences the difficulty and complexity of assessing and managing urban outdoor air pollution.

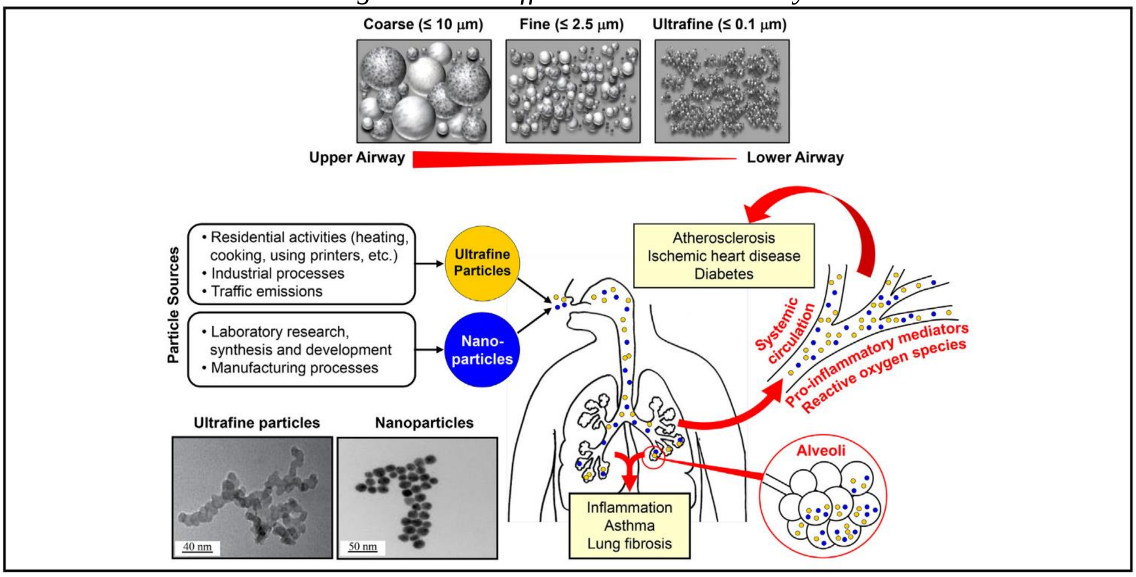
The WHO defines urban outdoor air pollution as the pollution experienced by populations living within and at the surroundings of an urban area (WHO, 2014). Regardless, people who are exposed to urban environments not necessarily reside in the same area, which in most cases represent the reality of a large urban metropolis. Urban areas are not only high density in terms of population and land but also in terms of infrastructure and built environment. North America and Scandinavian countries like Denmark, Finland, Norway, and Sweden designate urban areas. The authorities consider an urban area to have a minimum density of 400 people per square kilometre considered urban (Demographia, 2017). This may differ according to the national and/or regional context of a determinate area.

Urban areas represent an economic, cultural, financial, commerce, and mobility hub which make them essential for a country's development as regional and local productivity implies (Cottineau, Finance, Hatna, Arcaute, & Batty, 2016). Globally, circa 60% of the world's population lives in urban areas whilst in Europe two thirds of its population lives in towns and cities (UN, 2016; WHO Regional Office for Europe, 2018). While this tendency tends to increase in the following years, it is certain that urban areas pose major exposure for people to the related air contamination and must take accountability on AQ to ensure quality of life to its citizens.

Standards for Air Pollution are set for different types of contaminants such as ground level Ozone (O_3), Particulate matter (PM_{10}, $PM_{2.5}$), Carbon monoxide (CO), Lead (Pb), Sulphur dioxide (SO_2) and Nitrogen dioxide (NO_2). Pollutants like Ozone (O_3) and Particulate matter (PM_{10}, $PM_{2.5}$) are the result of chemical reactions happening between pollutants. Primary PM is directly emitted, while secondary PM originates from gaseous precursors. Primary pollutant emitted during combustion NO when oxidized yields NO_2 as secondary (EPA, 2018b).

Even though all of the mentioned pollutants are heavily linked with human diseases, Particulate matter (PM_{10}, $PM_{2.5}$) has found to be one of the most commonly dangerous, affecting the respiratory and even cardiovascular systems. This pollutant has caught attention due to its severe and long lasting impacts on human health. The fine particles or smaller than <2.5 microns contribute to breathing problems and lung damage while the larger <10 microns for vision, degradation of materials and impacts to vegetation (Trasportation Association of Canada, 2004). Particulate matter is also linked with pre-mature mortality from heart attack, stroke and lung cancer and is classified by its aerodynamic diameter to serve as an indicator for AQ as in smaller than 10 or 2.5 microns; PM_{10} and $PM_{2.5}$ consecutively (WHO, 2018b). The latter, $PM_{2.5}$, was found to be the main cause of reduced visibility in some regions of the United States (US EPA, 2016). Anthropogenic and natural sources contribute differently to loads of PM. Primary and secondary particulate matter contains a wide array of metals and toxins, which have carcinogens and are the cause of chronic obstructive pulmonary decease. The smaller the particle, the larger the threat they pose either by inhalation or penetration on the skin. On the following figure, a schematization of this is shown:

Figure 3 - PM effects in the human body

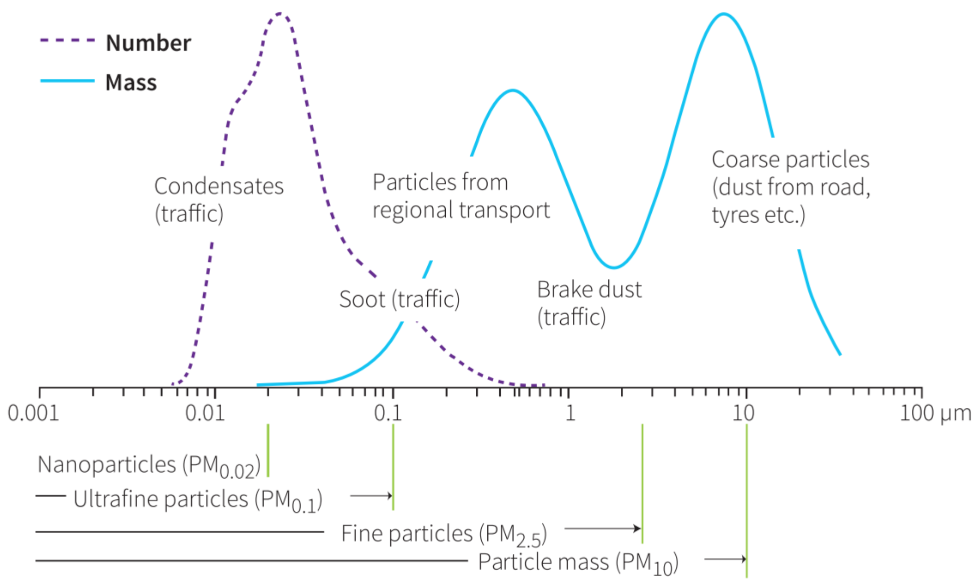


Source: (Li et al., 2016)

Ultrafine particles and nanoparticles can effectively deposit in the alveolar space in lungs and can be transported by lung cells to draining lymph nodes or translocate to distant organs through the bloodstream which can have adverse systemic health effects in many other organs. Studies have even pointed out that smaller particles can penetrate intracellularly and potentially cause DNA damage (Li et al., 2016). On the following table, types of PM are described and the figure explains the relation between mass and number of particles in the air:

Figure 4 - Types of PM

Particle type	Nomenclature	Aerodynamic diameter	Source
Coarse particles	PM_{10}	≤ 10 µm	Construction, mining, unpaved roads, farming activities
Fine particles	$PM_{2.5}$	≤ 2.5 µm	Combustion of solid or liquid fuels, power generation, industry, domestic heating and in vehicle engines
Ultrafine particles	UFP	< 0.1 µm or 100 nm	Combustion, diesel exhaust particles, products of cooking, heating and wood burning in indoor environments
Nanoparticles	NP	< 0.05 µm or 50nm	Engineered nanomaterial, nanotechnology manufacturing



Source: (Kinsey, Muleski, Cowherd, & Kinsey, 2017; Li et al., 2016; US EPA, 2016)

Later, health issues arise when large populations of an urban sprawl and large exposures to urban outdoor air pollution coexist. When it comes to urban areas, many studies have proven they are far from being the desired healthy places one would like to breathe in. The main characteristics usually attached with an urban area are heavy traffic jams, smog, noise, violence and consequently, social isolation phenomena for elderly and young people are perceived (WHO Regional Office for Europe, 2018). The need to the reduction of air pollution levels and its potential harmful effects on human health was also clearly emphasized in the Directive on ambient AQ and cleaner air for Europe (EU, 2008). At a worldwide level, the concern is Carbon dioxide (CO_2) and gases contributing to global warming, whereas for Denmark the current focus are population exposure to particle pollution, and deposition to sensitive parts of the countryside and to marine areas (Department of Environmental Sciences, 2018).

Stationary and mobile sources of pollution can be found in this type of urban environments. The most important scenario regarding the causes and more specifically, health attached sources of air pollution in an urban environment are the ones derived from poor combustion of fossil or biomass fuels (WHO, 2014). On one hand, exhaust emissions coming from motorized vehicles, furnaces, or rudimentary technologies used for cooking, heating, and lighting are the most common sources. On the other hand, industry as in manufacturing facilities and power generation can also collaborate with emissions and each particular scenario has to be carefully assessed. Here, indoor and outdoor air pollution relation could be extremely relevant when one type could be contributing to the other and vice-versa.

In Denmark, fireplaces are commonly known as part of the Danish 'hygge', providing a sense of cosiness at home. While this can be positive, brændeovne or wood burning stoves also account for an important part of particulate emissions. Danish households use these types of stoves to heat their homes or cottage. The last inventory found approximately 670 000 wood burning stoves in the country. Aalborg is listed as the third municipality from the highest to the lowest with 18 205 burning stoves in the municipality (Miljøstyrelsen, 2018b). In 2013, the DCE allocated percentages to the largest source of pollution in Denmark. The values given to PM2.5 was 67% contributed by wood burning as seen in the following table:

Figure 5 - Danish emission ceilings

Ceilings for Denmark	SO_2	NO_X	NH_3	NMVOC	$PM_{2.5}$	Methane
2010: Present NEC Directive (actual ceilings in tons/year)	55,000	127,000	69,000	85,000	---	---
2030: New NEC Directive (suggested new ceilings in tons/year)	10,000	58,000	46,500	47,000	9000	205,000
Danish emissions in 2011 (tons/year)	13,901	125,532	66,513	81,432	23,196	261,600
Largest source of pollution (% of total emissions in 2012)	Energy & industry (47%)	Transport (47 %)	Agriculture (96%)	Solvents (33%)	Wood burning (67%)	Agriculture (75%)

Source: (The Danish Ecological Council, 2014)

As stated before, Particulate matter (PM_{10}, $PM_{2.5}$) could be emitted directly from a source such as construction sites, unpaved roads, fields, smokestacks or fires. Also, they can be the result from complex reactions in the atmosphere from direct emissions coming from industry, power plants, or traffic such as the ones happening with sulphur dioxide (SO_2) and nitrogen oxides (NO_x) (US EPA, 2016). The Environmental Protection Agency of the United States regulates inhalable particles (diameter <10 micrometres) which are listed in the National Ambient Air Quality Standards (NAAQS) required by the Clean Air Act. The adopted Air Quality Directive in 2008, Directive 2008/50/EC included new regulations for Particulate matter ($PM_{2.5}$), concerning exposure concentration obligation and exposure reduction target.

Though many factors can be attached to poor AQ, transportation is a major contribution due to the burning of fossil fuels representing the largest contributor to carbon monoxide (CO), nitrogen oxides (NO, NO2) and Volatile Organic Compounds (VOCs)

(Trasportation Association of Canada, 2004). Specific gases/pollutants attributed to transportation engines have been studied due to its impacts towards human health. The WHO guidelines on AQ are based on accumulated scientific evidence and are designed to offer guidance towards reducing health impacts of air pollution. The guidelines emphasizes the importance of the knowledge on what sources contribute to human exposure and by how much with AQ guidelines for Particulate matter (PM), Ozone (O_3), Nitrogen dioxide (NO_2) and Sulphur dioxide (SO_2) as the following table describes (WHO, 2018b).

Table 2 - WHO Ambient AQ guideline

Pollutant	Indicator	Unit	Averaging period
Particulate Mater	$PM_{2.5}$	10 µg/m^3	annual mean
		25 µg/m^3	24-hour mean
	PM_{10}	20 µg/m^3	annual mean
		50 µg/m^3	24-hour mean
Ozone	O_3	100 µg/m^3	8-hour mean
Nitrogen dioxide	NO_2	40 µg/m^3	annual mean
		200 µg/m^3	1-hour mean
Sulphur dioxide	SO_2	20 µg/m^3	24-hour mean
		500 µg/m^3	10-minute mean

Source: (WHO, 2006)

Additionally, an overview of the limit values proposed by the Directive 2008/50/EC of the European Parliament on ambient AQ and cleaner air for Europe are described as the following:

Table 3 - WHO Ambient AQ guideline

Pollutant	Averaging period	Limit value	Maximum number of exceedances
Sulphur dioxide	Hourly	350 µg/m^3	Not to be exceeded more than 24 times a calendar year
	Daily	125 µg/m^3	Not to be exceeded more than 3 times a calendar year
Nitrogen dioxide	Hourly	200 µg/m^3	Not to be exceeded more than 18 times a calendar year
	Yearly	40 µg/m^3	-
Carbon Monoxide	Maximum daily eight hour mean	10 mg/m3	-
Particulate matter (PM_{10})	Daily	50 mg/m3	Not to be exceeded more than 35 times a calendar year
	Yearly	40 mg/m3	-
Particulate matter ($PM_{2,5}$)	Yearly	25 mg/m3	-
Ozone	Maximum daily eight hour mean	120 mg/m3	-

Source: (EU, 2008)

Regarding emissions related directly with transportation some research has been done aiming to assess human health exposure. Even though there is limited evidence on the direct impacts of air pollution on human health due to the complexity of its assessment, current and past research have studied the potential negative implication of air pollution on active mobility users. Particle matter exposure was analysed in cyclists during rush hour in a high-traffic intensity setting. While the associations between air pollution exposure and health were negative for the cyclist sample, the changes were not significant (Strak et al., 2010). In a Danish study, data was compiled on physical activity in a residential area and AQ for more than 10 years (Andersen et al., 2015). Regardless, the findings of studies on high level of traffic-related pollution and human exposure did not expose relevant criteria to conclude implications on human health; the research had its own limitations on sample size or timeline considerations. Additionally, whilst short-term exposure may conclude no relevant evidence, long-term effects on human health are still needed to be assessed. Facts that further evidence the need for replication in other populations (Andersen et al., 2015; Strak et al., 2010) contemplating groups of more vulnerable individuals (McCreanor et al., 2007). The previous, meaning the analysis of specific impacts on most vulnerable society targets as elderly, children and people with pre-existing respiratory and/or cardiovascular disease. In summary, people to whom outdoor urban air pollution may represent an increased risk is not touched. Evidently, a consistent void in experimental literature and studies for street-level air pollution exposure and active mobility is noticed.

In an urban area on the other hand, construction sites are considered as primary pollution sources where its operations have a direct and indirect affectation on AQ due specifically to particulate matter (PM_{10}, $PM_{2.5}$). Activities related with air pollution within this sector are the following: earthworks, superstructure building and finishing phases. Additionally, construction activities often if not always include emission from exhaust diesel engines embedded in trucks and/or machinery which is directly related with (NO_x) emissions (Cheminfo Services Inc, 2005). Several studies have demonstrated the impacts and effect on ambient outdoor air pollution coming from construction sites (Araújo, Costa, & Moraes, 2014; Dement et al., 2015; Kinsey et al., 2017) which have concluded increasing concentration of particles in construction sites surroundings and neighbouring locations. Additionally, studies on construction workers health related with the direct exposure to air pollution show an important percentage of chronic obstructive pulmonary disease (GOPD) can be attributed to construction-related exposures. The research also shows the following occupational exposure agents: coal dust, asbestos, silica, welding and cutting gases and fumes, cement dust, diesel exhaust, spray painting, organic solvents, and possibly man-made mineral fibres (Dement et al., 2015). Research with this regard is also scarce due to the nature of construction and its variability.

All of the above considered, AQ monitoring networks providing real-time data can represent the starting point enabling localized air pollution impact assessment. The data opens itself endless opportunities for research and evaluation of specific scenarios relevant for academia, public administration, industry or citizens on an individual level.

Air quality metrics, monitoring and geo-visualization - Many studies have tried to calculate the contributions of different local pollution sources at a global level with the vision of creating a systematic analysis (Karagulian et al., 2015). While others were created in order to fill gaps existing in literature to match concentrations to possible and potential urban AQ pollutant sources from heavy trafficked roads (Karner, Eisinger, & Niemeier, 2010). While these approaches can be done in a global, national or regional level, AQ can vary widely from block to block. Primary air pollutant concentration in cities and urban areas can vary sharply over relatively short distances (from 0.01 to 1 km) (Apte et al., 2017). Characteristics such as unevenly distributed emission sources, dilution, physicochemical transformations (Apte et al., 2017; Karner et al., 2010; Marshall, Nethery, & Brauer, 2008), atmospheric condition, seasonal and temporal variations and type of infrastructure present in the urban area alter pollution patterns widely. Hence, the importance of the assessment and monitoring of AQ on a local and specific level responding to specific conditions of space and time.

A few cities worldwide have implemented AQ monitoring networks since it represents an expensive and extensive, resourceful type of investment in which the outcomes are intangible and might only be seen in the long run. According to the WHO, many of the cities expected to be among the most polluted ones do not collect information or report data on its outdoor AQ which makes comparison at city level practically impossible (WHO, 2014), phenomena that is seen not only in low income but even in high income regions (Apte et al., 2017). Some cities though, have demonstrated commitment to address urban outdoor air pollution and consequently the related issues regarding public health. Air pollution has consequently become a growing concern triggered in part by acute air pollution episodes in cities worldwide such as the famous London, United Kingdom smog in 1952 or in the Meuse Valley, Belgium in 1930 (Hertel, Ellermann, Nielsen, Steen, & Jensen, 2015).

Methodologies and models have been used in order to understand spatiotemporal variability of outdoor urban air pollution such as satellite remote sensing (RS), chemical transport models (CTMs), land-use regression (LUR) models (Marshall et al., 2008) or direct personal exposure measurements have been used for the accountability of AQ. Other developments have been seen regarding AQ models, for instance, the Environmental Protection Agency of the United States developed a community multi scale open source AQ model (CMAQ) that incorporates three kinds of models: meteorological, man-made/naturally-occurring emissions, and air-chemistry pollution transport into one simplified model (EPA, 2016). The most notorious differences between these types are certainly levels of precision, resolution and feasibility of implementation, each one being characterized by different advantages and limitations. Nevertheless, as experts emphasize, the outcome of these types of models can only be limited for a certain period of time resulting in an inability to perform air pollution prediction of distribution or real-time response towards a specific scenario. With this, the necessary analysis/monitoring of local air pollution and its distribution variation are notoriously important and could be used as a tool to develop effective reduction initiatives. The improving of monitoring and assessment of AQ including the deposition of pollutants and to provide information to the public is required for member states of the European Union (EU, 2008). In the Directive on Ambient Air Quality and Cleaner Air for Europe, the importance on combating emissions of pollutants at source and to identify and implement the most effective emission reduction measures at local, national and community level is stated. The key for this so called identification and implementation could be metrics. Corrective actions can only take place if constant monitoring and accountability within a specific matter is reached. As the Directive 2008/50/EC mentions, identification is the first crucial step to take action, and assess it during time vital for effective outcomes.

Cases - Cities, as complex systems when mapped become visual understandings of the challenges they face and further represent a baseline to analyze the interrelations amongst transportation, environment, energy and others. Due to the growing concern on air pollution, cities are using the Internet of Things (IoT) platform in order to increase their monitoring range and make their process more efficient. That is how cities are deploying connected sensors to obtain the data needed to track and monitor relevant parameters, AQ amongst them. These types of developments are now known as the monitoring of the city's vitals. According to Bousquet, there are three models in which these type of initiatives fall and are the following:

Table 4 - AQ Monitoring Models

Air Quality Monitoring Model	**Pros**	**Cons**	**Real case example**
Adding high cost sensors to existing infrastructure	○ Data quality ○ Tracking data over time ○ Real-time data	○ High cost ○ Localized monitoring stations	Infrastructure embedded and fixed AQ sensors
Deploying low cost mobile sensors	○ Low cost ○ Citywide data collection	○ Cannot track AQ over time ○ No real-time data	Sensors attached to mobile structure (cars, bicycles, pigeons, etc.)
Personal devices data	○ Overview of resident exposure to AQ conditions	○ Pairing with existing sensors required	Mapping residents routes using anonymised cell phone data and matching it with AQ data

Source: (Bousquet, 2017)

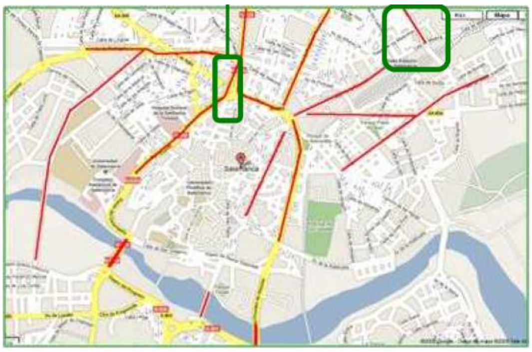
The RESCATAME project - 2011 held in Salamanca city primary goal was to achieve sustainable management of the traffic by using an AQ sensor network. The outcomes were expected to help define a new "Urban Traffic Management and Control Strategy" based on the prevention of regular high pollution episodes through the use of prediction models. The project is based on the Instrumented City concept piloted in the city of Newcastle which allows traffic and AQ to be analyzed in real time to produce pollution prevention by prediction.

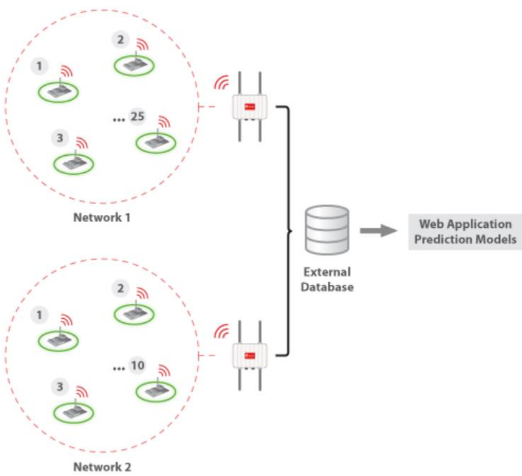
The usage of the concept enables the calculation of pollution in multiple scenarios and thus fine-tuned control measures for the city of Salamanca. Solar panels and batteries were adapted to wireless sensors and deployed throughout the city in high polluted areas. AQ was gathered on the course of one year and based on it, the prediction models estimated the values for the next one and three hours for the traffic department to foresee potential episodes and act accordingly without surpassing pollution thresholds.

As the CTT2.0 project, the reports denote the versatility of the network to be adaptable for different spatial scales, sectors and types of pollutants. The project finalized with the aim of extending coverage of the network and called the interest from other cities within and outside Spain (Camarsa et al., 2014).

Figure 6 - Salamanca's RESCATAME Project layout

Sensors Location[1]	**Sensors Architecture**[2]

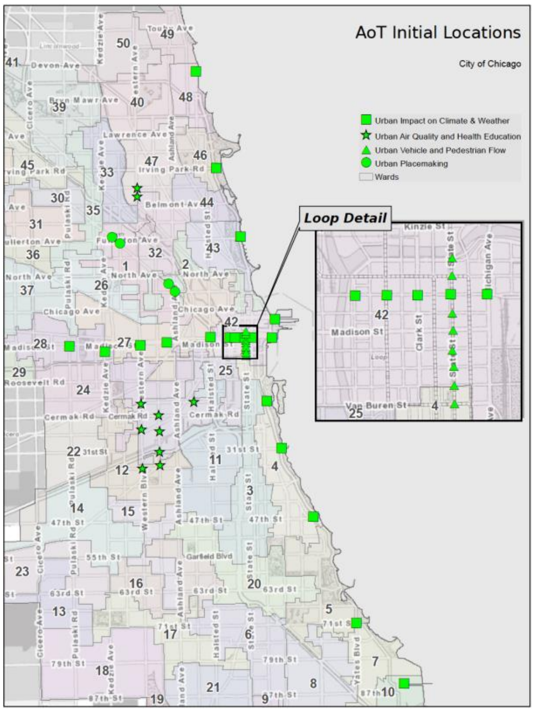
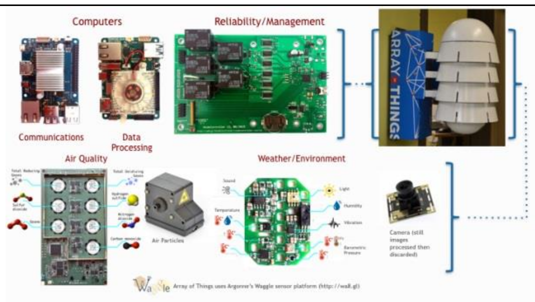


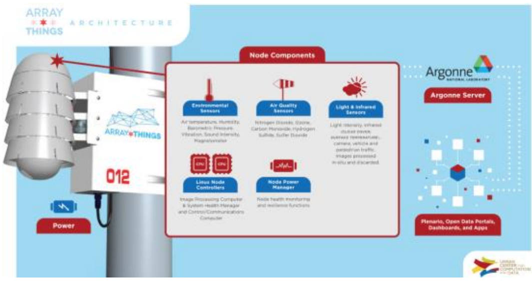


(red line)	Salamanca high traffic congestion areas
(green box)	Álvaro Gil & Avenida de los Cipreses St.

Source: [1](Gómez, Sastre, & Hidalgo, 2010), [2](Bielsa, 2011)

Chicago deployed its Array of Things (AoT) project as a collaborative effort with academia, scientist, government, and community in order to collect data on environmental parameters. The network deployment of a variety of sensors started in 2016 and will be finished this present year. Open data is the hallmark of this project, with collaboration of the University of Chicago the data will be hosted in a data portal available for all. As part of the project disclosure, stakeholders – residents, scientists, policy makers - were invited actively to contribute not only with questions and recommendations but with suggested usages of the data so the data can be prepared and tailored for those certain purposes. By publishing the data, the AoT aims to create baselines for academia and its research on urban problems. Besides, research for civic technologies and the creation of new products/businesses. For the community in general, the project aims to support decision making and improved quality of life (Array of Things 2016, 2016).

<table>
<tr><td colspan="2">Figure 7 - Chicago's Array of Things Project layout</td></tr>
<tr><th>Sensors Location</th><th>Sensors Architecture</th></tr>
<tr><td>
</td><td>

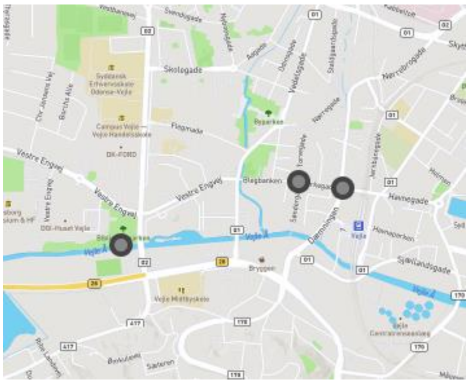

</td></tr>
<tr><td colspan="2">Source: (Array of Things 2016, 2016)</td></tr>
</table>

Carbon Track and Trace 2.0 (CTT2.0) deployed in 2016 is a Norwegian project intended to provide cities with real-time greenhouse gas (GHG) measurement capability. The project denotes the advantages of low cost open source sensors against traditional methods for GHG emission inventories by cost, time-effectiveness and most importantly its questionability on supporting decision and planning support processes. The project deployed pilot wireless environmental monitoring sensor networks upon Trondheim city in Norway and Vejle city in Denmark which data feeds a number of applications.

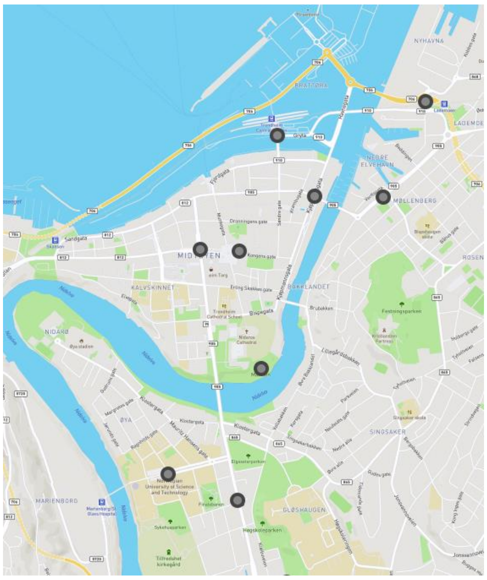
Dataport is a webpage application in which the visualization of the network and the health of the IoT connected devices are shown; the interface is to become an alerting system in the future. AQ data is stored and analyzed through a coded subsystem which was compared with the official Norwegian Air Quality Research Institute in order to show correlations; traffic data was also correlated for Vejle. Additional 3D geo-visualizations were also applied for the AQ data. The project concluded with successfully implemented networks in both cities emphasizing the flexibility and opportunities ahead with the usage and continuous improvement of the networks (Ahlers & Driscoll, 2016).

Figure 8 - Vejle and Trondheim CTT2.0 Project layout

Sensors Location

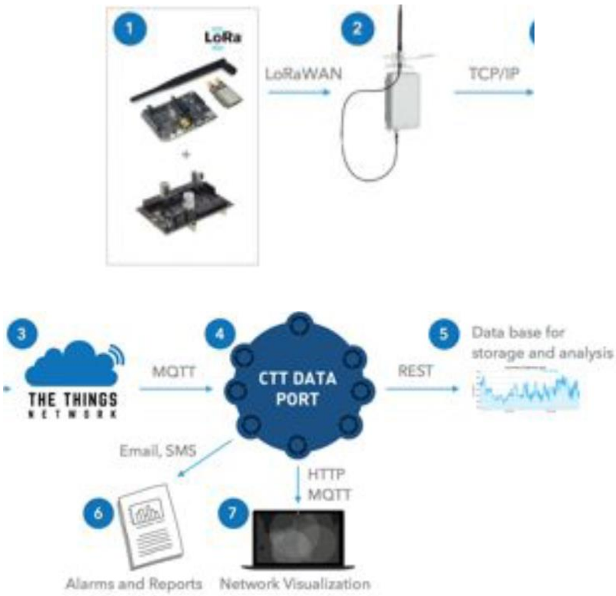


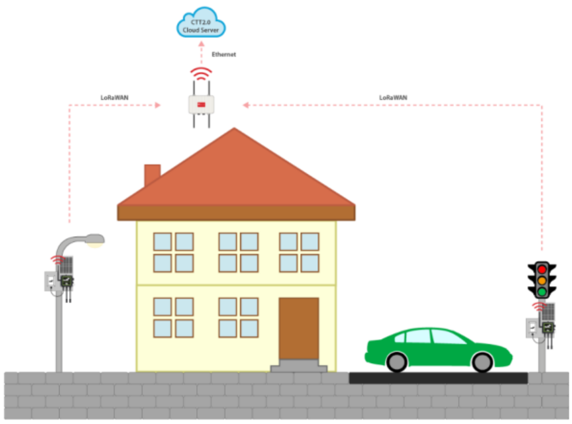
Vejle[1]



Trondheim[1]

Sensors Architecture





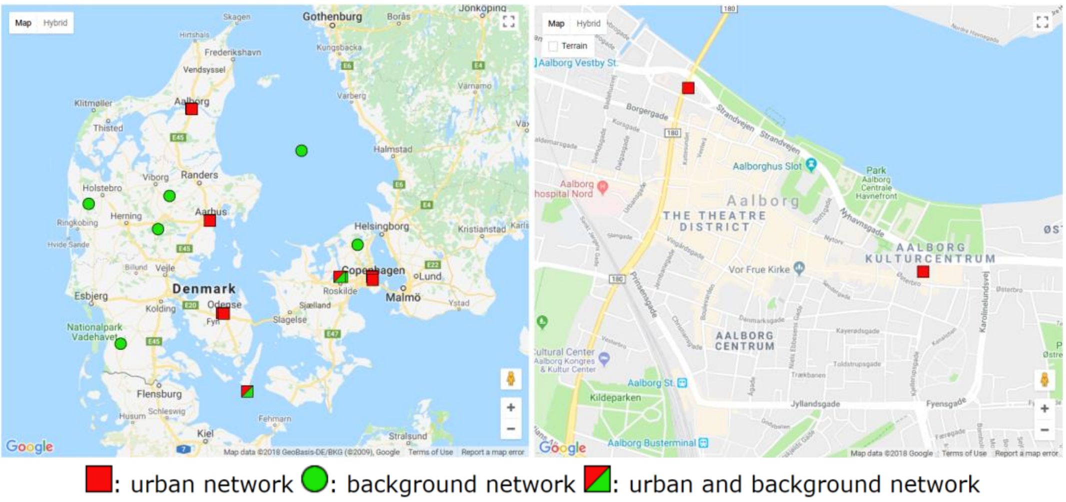
Sources: [1](NTNU, 2016), [2](Libelium, 2016)

On a national level, Air Now is an United States of America online platform in which every day Air Quality Index (AQI) data is available; Ozone and Particle Matter pollution data is translated into numbers or colours in order to make the information assimilation easier for the targeted user. AirNow data is collected through thousands of monitors allocated along the country's cities; the 24-hour basis concentrations are converted into an hour basis and then translated into AQI. The goal of this initiative is to provide the public awareness on AQ with easy access to national AQ information in order for them to take action. Regardless, the data is used only to report AQI, not to support policy or decision making at any regulatory level. Based on this data, Air

Quality Flag Program targets agencies or community organizations, encouraging them to notify through flags harmful air conditions to the inhabitants in order to enhance their decision making. Apart from real-time data, these programs also contemplate daily forecasts based on analysed patterns and the information is further disclosed through technological tools such as API and geo-visualization maps embedded in official web pages (AirNow, 2016).

In Denmark, the DCE is Aarhus University's unit for knowledge exchange within areas regarding nature, environment, climate and energy. Here, air pollution is a high priority; the unit conducts internationally recognized research of high quality. The university manages the national Danish data reporting in accordance with local and international standards. The expertise in AQ monitoring of the university is based on the combination of measurements of official stations and model calculations to describe and assess pollution and its further impact on the environment. DCE provides consultancy services for the Danish Ministry of Environment and carries the national monitoring for AQin Denmark through the usage of a network of monitoring stations supplemented by modelling. AQ data measured with automatic stations is updated every hour and available to the public (Department of Environmental Sciences, 2018; Ellermann et al., 2017a). In the following image, the street, urban and land AQ monitoring stations for Denmark are shown.

Figure 9 - Danish AQ Monitoring Programme stations



Source: (DCE, 2017)

Based on this monitoring, the university unit created the AQ at Your Street project. The project ran from 2012 until 2016 and aimed at the development of a public digital local AQ map including annual concentrations for NO2, PM2.5 and PM10 based on a multi-scale AQ modelling approach. The model used a chemistry-transport approach developed by the research unit including regional modelling, urban background and street modelling. Traffic data is also contemplated based on the Danish Transport Model. The data was contrasted with the data obtained from fixed site monitoring stations under the Danish Air Quality Monitoring Program (DCE, 2012).

In the previous examples from all over the world, a common principal target which is general public information and awareness on AQ levels is spotted. A combination of techniques is used involving real time and projection through modelling of air pollution. Furthermore, the possibility for authorities and related stakeholders to make use of the provided data for the enhancement of their performances and services is seen.

Challenges of low cost air quality sensors - Amongst the literature reviewed, there is an increasing spoken concern regarding AQ data reliability obtained from the low cost AQ sensors. When testing a study with 20 commercial packets of sensors which were compared with standard measurement and a report of the degree of agreement between both was made. The outcomes denoted mixed results for the different types of gases that were tested and also data correlation with certain statistical methodologies. The study concludes implying that the state-of-the-art of this technology should at best be considered as a “work in progress” depending on the type of gas or parameter is being assessed. Extensive laboratory testing is recommended along with needed research of numerical strategies to correlate and correct the measured values (Lewis et al., 2016).

Another study denotes the possibilities of these ubiquitous sensing networks that were not feasible just a few years ago. Commercial air pollution sensor calibration processes often go against standard analytical methods, leaving a precision ranging within ±10% for most air pollutant measurements which evidently needs to improve. Another aspect is the non-expertise knowledge required is one of the hallmarks of these sensors which have given birth to public participation and community based AQ monitoring. Challenges for this so called techno-economic matter include improving the quality of the measurements while reducing cost specifically related to maintenance and data management which in some cases exceeds the cost of the hardware. It is also stated that awareness, education, and technology will have to mature together with regards to air pollution ubiquitous monitoring networks (Kumar et al., 2015).

Studies in general denote the challenging nature of accurate AQ measurements on having stability over time and a usable degree of accuracy (Kumar et al., 2015; Lewis et al., 2016; Mead et al., 2013). It is stated that it will be challenging for low cost sensing to match the robustness of conventional stationary monitors, especially in the near future. Additionally, the studies acknowledge that the amount of published scientific work for verification purposes on these sensors is rather scarce. Here, particularly taking into account the global trend on data democratization and publicly available for amateur users. Experts call for full analytical evaluation of these low cost AQ sensors specifically using real world pollutant quantities and its respective interferences. Caution is recommended especially when the data obtained by these sensors is to have a role in the management level of a city. For this, the specific intention has to be clearly determined when planning LCAQMSN. Additionally, responsibility on defining sensor usages and capabilities is allocated on manufacturers and regulator entity since they are to determine the data purpose. For Lewis this process has to come before bringing the public to the equation along with the acknowledgement of the technology limitation and strength.

Taking into account a life cycle perspective, low cost sensors are considered to have a fairly short life expectancy. At the same time, sensors have the potential of becoming an e-waste burden after their respective cease of operations. This research evidences the greatest tendency on sensor deployments not only aimed for environmental monitoring purposes but for other urban concerns and therefore the amount of devices needed to obtain a citywide range. This clearly emphasizes the need for an extended and detailed carbon footprint analysis along with the sustainable management of their maintenance and proper disposal of potential harmful materials embedded on the sensors.

3.2 Smart sustainable cities and its metrics

Smart sustainable cities - The smart city concept proposes a deep focus on the citizen and allocates its efforts onto the improvement of people's quality of living. Cities walking towards proper management have the urge to be smart (Novikov et al., 2015). Before the current century, technology was not always in the palm of our hands. In fact, only few corporations were able to afford certain types of technology, and it hasn't been that long since telephones were replaced by smartphones, bulky desktops by portable laptops and currently humans coexist with self-driven vehicles (Moreno, 2018). This affordability and accessibility twist has certainly made the opportunities of this technology escalate to a city management level. Devices and sensors, both private and public are connected to the Internet of Things (IoT) and grow exponentially as years go by; these are the feeders of what now is called Big Data.

Businesses and organizations worldwide have been using the term to call innovative solutions or processes including the use of some of the nowadays available technology. The term has also gained name as a sustainability strategy for cities since their implementation benefits include resource efficiency enhancement, multidimensional approach, and smart allocation of resources along with real-time environmental monitoring case studies.

Despite the efforts of a variety of authors around the globe searching for a common definition of a smart city (Rincón & Lehman, 2018), the term remains somewhat unclear due to its complex nature. The term and its application differ widely amongst different stakeholders. However, the application of the concept is the result of intertwined global trends which Birbi determines as the following three: the diffusion of sustainability, the spread of urbanization and the rise of Information and Communications Technologies (ICT) (Bibri, 2018). Cities are becoming data-driven monitoring behavioural patterns and assessing urban areas in order to enhance their services delivery (PricewaterhouseCoopers, 2016).

The European Commission defines a smart city as the place where traditional services are improved efficiently with the use of digital and telecommunication technologies with the aim to make cities more sustainable in view of Europe's 20-20-20 targets. It targets ICT, energy and transport to tackle traffic, air pollution, energy cost to achieve better mobility, cleaner urban environment, and energy efficiency (The European Commission, 2018). For development and economy, cities are indeed Gross Domestic Product (GDP) drivers, and certainly financial resource's urban farms. They are the consequence of rural migration and urban sprawl that predictions say will be continuously growing (UN, 2016).

On a management level, the interoperability amongst the different city management spheres is the real hallmark of the smart city which at the same time poses the greatest of challenges. According to research, only the integration of all city's domains based on the contribution of ICT can help cities to achieve long-lasting and sustainable economic growth while improving quality of life (Anthopoulos & Tougountzoglou, 2012). The potential of the synergies that could be obtained through the deployment of this type of technology requires proper management for the consolidation of the initiatives by each department. A constant monitoring and reporting system has to also be done, that's how cities around the globe have allocated the respective resources onto Smart City projects including a specific manager in charge to work with all the city's management spheres (Moreno, 2018). Experts suggest that this organizational interconnection is the driver for multiple short-term and long-term effects for the benefit of the city's major stakeholders. Jointed efforts from industry partners, central or national agencies, and scholars have achieved the integration of smart cities, focusing on urban life's dimensions enhancement (Bifulco, Tregua, Amitrano, & D'Auria, 2015).

Smart sustainable cities assessment - When it comes to the assessment of a smart city preparedness, literature containing certain guides available made by organizations worldwide is found (Giffinger, 2007; Smart City Council, 2015; UrbanTide, 2015). These guides propose assessment tools for the different city's administrations to understand their particular status in what they call "The smart journey" or "The smart transition". The major change from 2007 to date is that the categories for city responsibility has been broken up into different sub categories to reach a better, more meticulous and definitely holistic type of understanding on how the pieces of the city work together.

While these guidelines draw the baseline of what will be developed as the Smart City Roadmap, a profound and continuous analysis has to be placed with the input of each of the key stakeholders. The relevance of the assessment loses transparency if only one of the parties does not contribute or is isolated from the others. Plus, the nature of the guidelines makes subjectivity a noticeable threat for the validity and truthfulness of the assessment.

On the other hand, these components have to be based in tangible and measurable elements that quantify the failing or success of a certain measure. Here, the real importance of city's metrics. As suggested by Moreno, aside from the "what can be measured can be managed" controversy, metrics are the tool that could help a city separate from average to an enhanced and efficient performance (Moreno, 2018).

Even if a city's metrics can be subjective and somewhat intangible, cities can rely on international standardizations providing set of Key Performance Indicators (KPI's) for Sustainable Development of Communities as in the ISO 37120:2014. The first standard for a city level is composed by 17 themes for city services and quality of life and 100 indicators. This baseline represents a common infrastructure both for communication and measurement (Bodum, 2018), providing indicators and methodologies to monitor Sustainable performance in cities (Moreno, 2018).

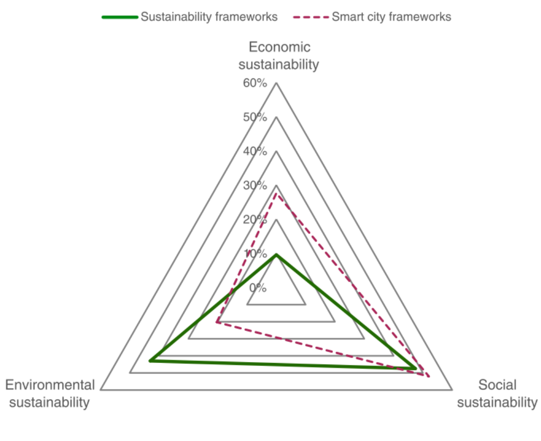
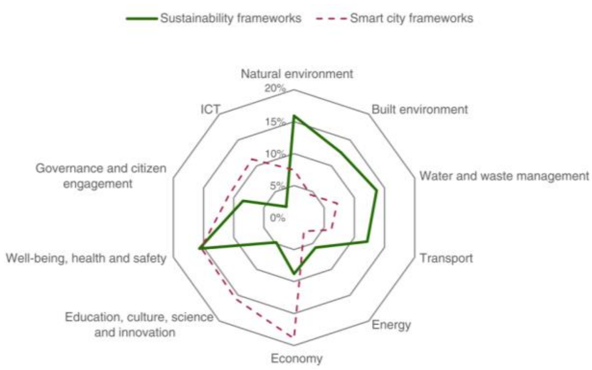
Literature also proposes the implementation of other KPI's as the one proposed by the CITYkeys project co-funded by the European Commission within the Horizon 2020 Programme or the ones proposed by Giffinger in the Smart cities Ranking of European medium-sized cities. The first proposal sets cross-sectorial KPI's intended to fit into a holistic and integral framework covering people, planet, profit, process and propagation (Bosch et al., 2016). Giffinger on the other hand covers characteristics such as smart economy, smart people, smart governance, smart mobility, smart environment, and smart living (Giffinger, 2007). Some KPI's are to be tailored for the specific situation and environment they plan to be evaluated. This consensus should also be obtained with all the stakeholders and the KPI's used are always tied to a certain goal, target or a specific objective (Bosch et al., 2016).

Regarding sustainability, as the author emphasized in her previous work, Smart Cities Leverage the potential of technology using it as a strategy for sustainable development (Moreno, 2018). At the same time, this relation also goes in the other direction where Information Communication Technologies (ICT) can be seen as the tools to enable the smartization process. Research considers ICT and sustainability as across-the-board elements for smart initiatives due to the central role they play while performing smart activities (Bifulco et al., 2015). Environmentally, a smart city enhances efficiency and responsibility in distribution and usage of cities resources and services. Socially, it fosters quality of life and wellbeing while economically; it fuels balance and equitable development (Etzion & Aragon-Correa, 2016; Hajduk, 2016; Novikov et al., 2015).

Now, even though sustainability is typically considered with three main key aspects – economic, environmental, and social – the understanding of the relationships between people, their activities, and the environment is key to achieve sustainability. And in that sense, technology could represent a major role. With technology, in the 21st century, a shift from sustainability assessment frameworks to smart city goals has been noticed (Ahvenniemi, Huovila, Pinto-Seppä, & Airaksinen, 2017). In the mentioned research, this difference is analysed. Both types of frameworks and its respective indicators were separated under sector and assessed in order to understand its differences and the impacts on the three pillars of sustainability.

The findings for smart frameworks denote that the social dimension covers more than half of the total number of indicators whereas environmental sustainability hardly less than a quarter and economic less than a third, suggesting priorization for social above environmental. On the other hand, urban sustainability frameworks distribute almost evenly social and environmental dimensions while focusing the minority of indicators for economic dimension. However, when the social dimension is classified by types of indicators meaning an accumulation of the three impact categories, a clear difference between both types of frameworks is seen. On one hand, smart frameworks focus their indicators towards economy, education, culture, science, and innovation. By the other, sustainability frameworks focus in natural and built environment, water and waste management, and transport. In the following table, descriptions of the analysed frameworks are shown.

Table 5 – Compilation of city's frameworks to assess sustainability and smartness

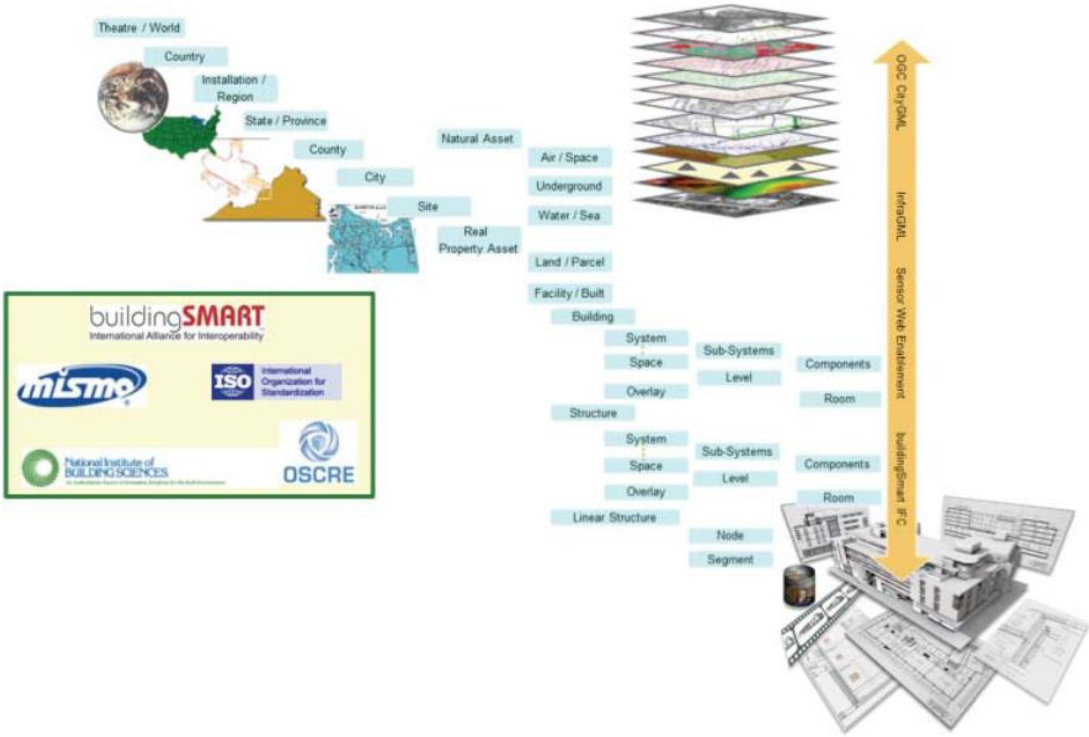
Analysis	
Smart city framework	**Sustainable city framework**
European Smart Cities Ranking	ISO 37120 Sustainable development of communities – Indicators for city services and quality of life
The Smart Cities Wheel	Reference framework for European sustainable cities (RFSC)
Bilbao Smart Cities Study	BREEAM Communities
Smart city benchmarking in China	LEED for Neighbourhood Development (LEED ND)
Triple-helix network model for smart cities performance	CASBEE for Urban Development (CASBEE-UD)
Smart City PROFILES	STATUS – Sustainability Tools and Targets for the Urban Thematic Strategy project
City Protocol	SustainLane
CITYkeys	UN Habitat indicators
Results	
Division of indicators according to sustainability's pillars	**Division of indicators according to sector categories**
	
Source: (Ahvenniemi et al., 2017)	

By this analysis, not only the clear gap between framework focuses is noted but also a certain complement between each other. With smart city frameworks focusing indicators on economic and social parameters while sustainable frameworks rather in environmental parameters, it could be suggested that sustainability assessment should form an active and core part of the smartness assessment and vice-versa. The complete assessment of both frameworks could seriously imply the monitoring of the necessary interoperability of resources and efforts towards a smart sustainable city.

Further, the majority of indicators found in literature involve geospatial technologies and in many of those cases geo-located sensors. Hence, the fact that spatial information technologies act as indicator support, going further than communicating and calculating. Geospatial analysis represents a potential efficient visualization which enables planning, development and public leadership (Open Geospatial Consortium, 2015).

This only emphasizes the power of the location; especially when aiming the analysis of several parameters forming part of the city system. These parameters can be analysed and identified layer by layer with the help of geospatial technologies reaching a truly holistic approach. The OGC proposes several examples of these types of implementation. The calculation of outdoor recreation space indicators to noise pollution through the use of models such as INSPIRE Building Model based in open standards such as CityGML. The Consortium emphasizes the primary and pervasive role that spatial information plays for Smart Cities and the interoperability of its services which can be seen in the graphic below.

Figure 10 - OGC's spatial data modeling across Standards Development Organizations



Source: (Open Geospatial Consortium, 2015)

4. Document and geospatial analysis

4.1 Document analysis

4.1.1 Low cost air quality sensors specifications

The available sensors correspond to Libelium Smart Environment PRO WASPMOTE Plug & Sense series sensors. Libelium is an international technological company designing and manufacturing hardware. The company offers a complete software development kit for wireless sensor networks. This way, system integrators, engineering, and consultancy companies can deliver reliable Internet of Things and Smart Solutions with minimum time to market. The scope of projects reachable with these types of sensors goes from measuring radiation levels in Fukushima to Smart factories in Spain. The company is recognized due to its support in IoT revolution, providing tailored solutions to multiple sectors and connecting any type of sensor to any cloud platform using any type of wireless technology (Libelium, 2018).

A Waspmote is a wireless embedded sensor platform integrating Cloud Systems and low energy IoT connectivity protocols. Their technology has been used by multiple stakeholders in businesses and academia, including projects for monitoring traffic and environment in Smart Cities.

While Libelium offers 2 types of IoT sensor platforms, the Waspmote Plug & Sense line allows developers to forget about electronics and focus on services and applications for these devices. These lines of devices are built to deploy wireless networks in an easy and scalable way, what Libelium calls "out-of-the-box" ready (Libelium, 2017b).

The Department of Planning of Aalborg University made the acquisition of 7 sets of Libelium Smart Environment PRO WASPMOTE Plug & Sense. Each one is equipped with sensor probes to measure air pollution parameters in the city of Aalborg. The following table depicts the key characteristics of the platform and sensors to be used.

Table 6 - Libelium Smart Environment PRO WASPMOTE Plug & Sense specifications

Technical specifications	
Versatility	Easily add or change sensor probes
Battery	- Solar powered with external panel - External battery module
Radio	4G
Enclosure	- Robust waterproof IP65 - Special holders and brackets are allocated for installation in city public infrastructure
Programming	- Over the air programming (OTAP) via 4G - Graphical and intuitive interface Programming Cloud Service - Manual through Libelium's Integrated Development Environment for Waspmote (IDE)
Reset	External, contactless device reset with magnet
Modules	- GPS receiver - SIM connector

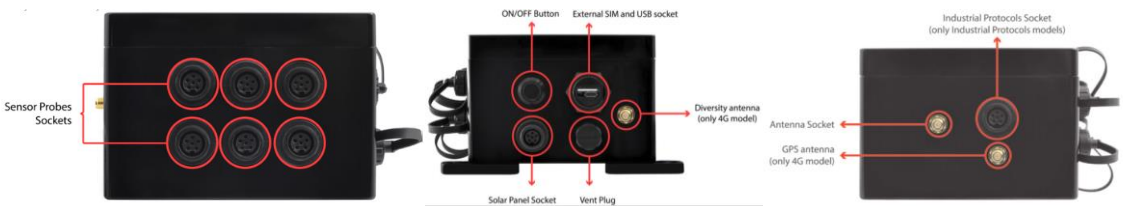
Physical specifications		
Materials	Polycarbonate, polyurethane, stainless steel, IP65, IK08, Heavy metals free,	
Temperature of Operation	- Ambient temperature (min.): -30 °C[1] - Ambient temperature (max.): 70 °C[1]	
Weight	800 g (only Waspmote) 2000 g (Waspmote + gases probes)	
Monitoring sensor probes, calibration and accuracy		
Probe	**Accuracy[2]**	**Range**
Temperature [Calibrated]	± 1 °C (± 0.5 °C at 25°C)	$-40\ to\ 85$ °C
Humidity [Calibrated]	$\pm 3\%\ RH$ $(at\ 25°C, range\ 20 \sim 80\%\ RH)$	$0\ to\ 100\%\ HR$
Pressure [Calibrated]	$\pm 0.1\ kPa\ (range\ 0 \sim 65\ °C)$	$30\ to\ 110 kPa$
Carbon Monoxide (CO) for low concentrations [Calibrated]	$\pm 0.1\ ppm$	$0\ to\ 25 ppm$
Carbon Dioxide (CO_2) [Calibrated]	$\pm 50\ ppm$ $\pm 200\ ppm$	$0\ to\ 2500 ppm$ $2500\ to\ 5000 ppm$
Nitric Dioxide (NO_2) [Calibrated] high accuracy	$\pm 0.1\ ppm$	$0\ to\ 20\ ppm$
Sulfur Dioxide (SO_2) [Calibrated] high accuracy	$\pm 0.1\ ppm$	$0\ to\ 20\ ppm$
Particle Matter (PM1/PM2.5/PM10)	Calibrated	$0.5\ to\ 16\ \mu m$
Gases calibration		

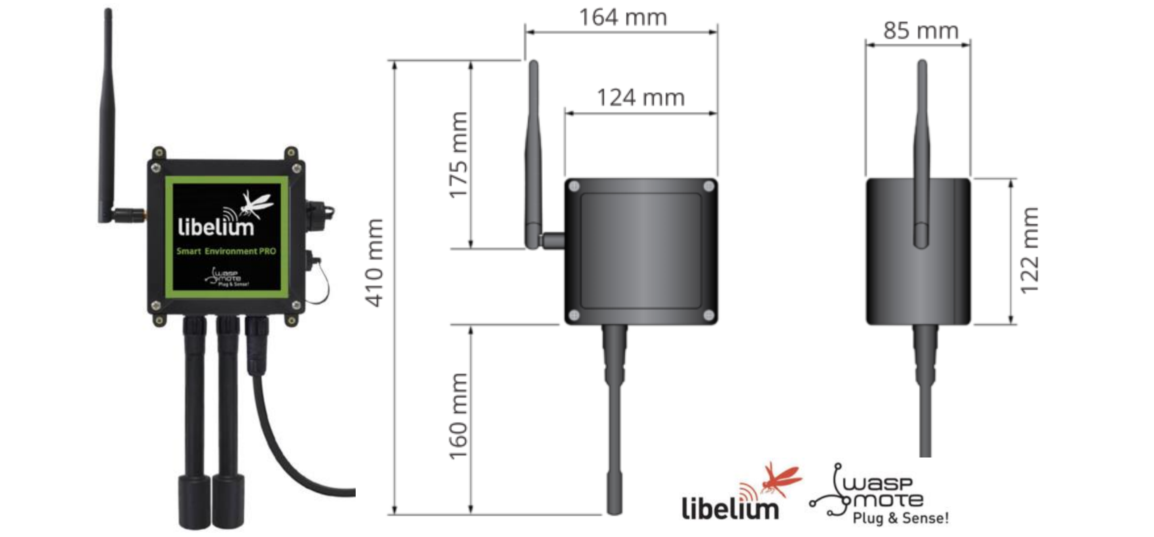
Temperature, Humidity and Pressure measurements are calibrated in factory with 3 calibration points for temperature, 6 points for humidity, and 9 points for pressure which are inter-compensated in order to obtain the measurement.

All the other sensors are calibrated in the manufacture's laboratories where a two-point calibration process is performed with controlled concentrations of gas in vacuum chambers. The sensors are linear behaving accordingly to $y = f(x) = mx + c$ as a simple line. Those 2 points correct the 2 possible drifts in m (slope) and c (constant offset).

The parameters are stored in a non-volatile memory chip inside each gas sensor. When a measure is performed, the software reads the sensor signal and both calibration parameters so they can process the system along with a temperature compensation calculation.

Cross sensitivities are including but not limited to the gases from the tables, it could respond to other gases.





[1]Regular recommended usage: -20, +60 °C, [2]Libelium indicates theoretical accuracy for an ideal reference. Maximum accuracy for each sensor is valid only for 6 months. All sensors loose a small percentage of calibration monthly in a range that may go from 0.5% to 2% (Libelium, 2017a).

4.1.2 Smart and Sustainable indicators

While justification and usefulness of city metrics has been already demonstrated in section 3.2, along with some case examples of the usage of technology for environmental monitoring, specific metrics are needed. Therefore, in order to acknowledge how these metrics are proposed by organizations; Key Performance Indicators (KPI's) are researched. Quantitative, qualitative or descriptive measurement is offered by a wide variety of indicators which should be tailored to the specific need. The framework suggests that the process of indicator selection requires a beginning baseline evaluation followed by a unanimous consideration of all stakeholders. The necessary presence of the related stakeholders is noted, in which the decision contemplates indicator's specificity, measurability and acceptability with regards to a certain environment.

Two main sources are used in this section. The ISO 37120:2014 for Sustainable Development emphasizes its efforts to provide standardized, consistent, and comparable indicators which could be used to monitor performances across cities. The ISO indicator classification respond to the following: economy, education, energy, environment, finance, fire and emergency response, governance, health, recreation, safety, shelter, solid waste, telecommunications and innovation, transportation, urban planning, and wastewater. CITYkeys project – together with all its collaborators - includes smart city project and corresponding indicators on a city level. The project indicators aim to identify the impact on time a certain project has had while the city indicates an evolution of the whole system in time. The categorization people, planet, prosperity, governance, and propagation are proposed for the smart city indicator framework.

Research has evidenced the need of a more holistic, integral, yet systemically oriented framework that can truly help cities monitor and track their actions in order to attain their objectives. While the ISO proposes indicators for an array of dimensions, its indicators are found to be objectively targeted to basic parameters which could be useful for an overview of current situation and basic monitoring along time. Clearly, as described by Ahvenniemi et al., environmental indicators are a big focus of sustainability assessment frameworks (Ahvenniemi et al., 2017). Notwithstanding, a complement to specific and technical indicators is vital for the analysis of the city's systemic nature. CITIkeys proposes a different categorization for a smart city assessment. The categorization is the final parameter the indicator is aiming to assess as in people or planet. On the specific indicators, a more qualitative approach is noticed.

Taking the scope of this research, indicators under the environment category indicate quantitative measurement of popular urban pollutants. By themselves, those indicators would only provide tracking of pollutants on a city level. This by nature averages a hyper-locally changing parameter and provides no insights to specific hotspots or critical areas in which air pollution could or could not represent a hazard. Now, regardless of their limitations, these indicators could be taken as control monitoring which other indicators could base their analysis with regards to. This analysis could be direct or indirect. For a direct example, urban pollutants vary when compared with annual number of public transportation trips per capita. Here, more trips per capita in urban transportation could represent a reduction in private transportation usage and therefore less air pollution. Indirect incidences require a broader analysis, for example, crime rate indicators at first sight could be not directly related with air pollution. Regardless, if assessed further, crime could be one of the reasons inhabitants chose a private over public transportation which could lead to increased trips made in private vehicles and further higher pollution.

The indicators have been presented according to the relevance of AQ and the possible positive/negative impacts the parameter might/might not have in relation to the other categories proposed. The indicators have been selected for the purpose of this research only, the presentation of these indicators under any circumstance should be considered as the only possible analysis of its interrelations. As proved by research, decision making on a management level has to rely on a multi-level analysis which therefore have to be supported by same ideology metrics. Aiming to compile cross-sectorial KPI's oriented to acquire the interoperability needed in order to develop smartness while engaging sustainability; some indicators are spotted to be of use and are listed below.

Table 7 - ISO 37120 and CITYkeys indicator list				
Indicator				
Category	**Subcategory**	**Found in**	**Name**	**Type**
Environment		ISO 37120	Fine Particulate Matter (PM2.5) concentration	Core
		ISO 37120	Particulate Matter (PM10) concentration	Core
		ISO 37120	Greenhouse gas emissions measured in tones per capita	Core
		ISO 37120	NO2 (nitrogen dioxide) concentration	Supporting
		ISO 37120	SO2 (sulphur dioxide) concentration	Supporting
		ISO 37120	O3 (ozone) concentration	Supporting
		ISO 37120	Noise pollution	Supporting
Planet	Pollution and waste	CITYkeys	Air quality index	-
Planet	Ecosystem	CITYkeys	Share of green and water spaces	City
Urban planning		ISO 37120	Green area (hectares) per 100 000 population	Core
		ISO 37120	Annual number of trees planted per 100 000 population	Supporting
		ISO 37120	Areal size of informal settlements as a percentage of city area	Supporting
People	Quality of housing and built environment	CITYkeys	Design for a sense of place	Smart project
		CITYkeys	Ground floor usage	City
Planet	Materials, water and land	CITYkeys	Population density	City
		CITYkeys	Brownfield use	City
		CITYkeys	Increase in compactness	Smart project
Recreation		ISO 37120	Square meters of public indoor recreation space per capita	Supporting
		ISO 37120	Square meters of public outdoor recreation space per capita	Supporting
Energy		ISO 37120	Total residential electrical energy use per capita (kWh/ year)	Core
		ISO 37120	Energy consumption of public buildings per year	Core
		ISO 37120	The percentage of total energy derived from renewable resources, as a share of the city's total energy consumption	Core
		ISO 37120	Total electrical energy use per capita	Supporting
Planet	Energy & Mitigation	CITYkeys	Annual final energy consumption	City
		CITYkeys	CO2 emissions	City

Transportation		ISO 37120	Kilometres of high capacity public transport system per 100 000 population	Core
		ISO 37120	Kilometres of light passenger public transport system per 100 000 population	Core
		ISO 37120	Annual number of public transport trips per capita	Core
		ISO 37120	Number of personal automobiles per capita	Core
		ISO 37120	Percentage of commuters using a travel mode other than a personal vehicle	Supporting
		ISO 37120	Number of two-wheel motorized vehicles per capita	Supporting
		ISO 37120	Kilometres of bicycle paths and lanes per 100 000 population	Supporting
		ISO 37120	Transportation fatalities per 100 000 population	Supporting
People	Access to other services	CITYkeys	Access to public transport	City
		CITYkeys	Access to vehicle sharing solutions for city travel	City
		CITYkeys	Access to public amenities	City
		CITYkeys	Access to commercial amenities	City
Prosperity	Competitiveness and attractiveness	CITYkeys	Congestion	City
		CITYkeys	Public transport use	City
		CITYkeys	Decreased travel time	City
Health		ISO 37120	Average life expectancy	Core
Safety		ISO 37120	Number of homicides per 100 000 population	Core
		ISO 37120	Violent crime rate per 100 000 population	Supporting
People	Health	CITYkeys	Encouraging a healthy lifestyle	City
People	Safety	CITYkeys	Traffic accidents	City
People	Education	CITYkeys	Environmental education	City
		CITYkeys	Digital literacy	City
		CITYkeys	Increased environmental awareness (P)	Smart project
Governance	Organization	CITYkeys	Cross-departmental integration	City
		CITYkeys	Establishment within the administration	City
		CITYkeys	Monitoring and evaluation	City
		CITYkeys	Availability of government data	City
		CITYkeys	Involvement of the city administration	Smart project
		CITYkeys	Clear division of responsibility	Smart project

		CITYkeys	Continued monitoring and reporting	Smart project
		CITYkeys	Leadership	Smart project
Governance	Community involvement	CITYkeys	Citizen participation	City
		CITYkeys	Open public participation	City
		CITYkeys	Professional stakeholder involvement	Smart project
		CITYkeys	Local community involvement in planning phase	Smart project
		CITYkeys	Local community involvement in implementation phase	Smart project
		CITYkeys	Participatory Governance	Smart project
Governance	Multi-level governance	CITYkeys	Smart city policy	City
		CITYkeys	Expenditures by the municipality for a transition towards a Smart city	City
Prosperity	Innovation	CITYkeys	Innovation hubs in the city	City
		CITYkeys	Open data	City
		CITYkeys	Research intensity	City
		CITYkeys	Accessibility of open data sets	City
		CITYkeys	Quality of open data	Smart project
		CITYkeys	Improved interoperability	Smart project
People	Access to other services	CITYkeys	Access to high speed internet	City
		CITYkeys	Access to public free Wi-Fi	City
Source: (Bosch et al., 2016; ISO, 2014)				

4.2 Geospatial analysis

4.2.1 Aalborg's city layout and public infrastructure

Through the geo-information sources and the Danish Web Map Services, data relevant on the city and its infrastructure was obtained. The data compiled is related to road classification, transportation network, parking lots, residential, commercial and industrial areas, green areas, trees, and vegetation. Map1 shown below depicts the combination of the ArcGIS shapefiles acquired on urban Aalborg.

Map 1 - Aalborg layout and public infrastructure

Source: (Erhvervsstyrelsen, 2018; ESRI, 2016; OIS, 2018; Open Data DK, 2015; Styrelsen for Dataforsyning og Effektivisering, 2018)

In addition, the city's most important urban development areas are shown in Map2. A large development is expected within the central urban area of Aalborg and Norresundby, next to the major corridors of the city (M. Jensen et al., 2015).

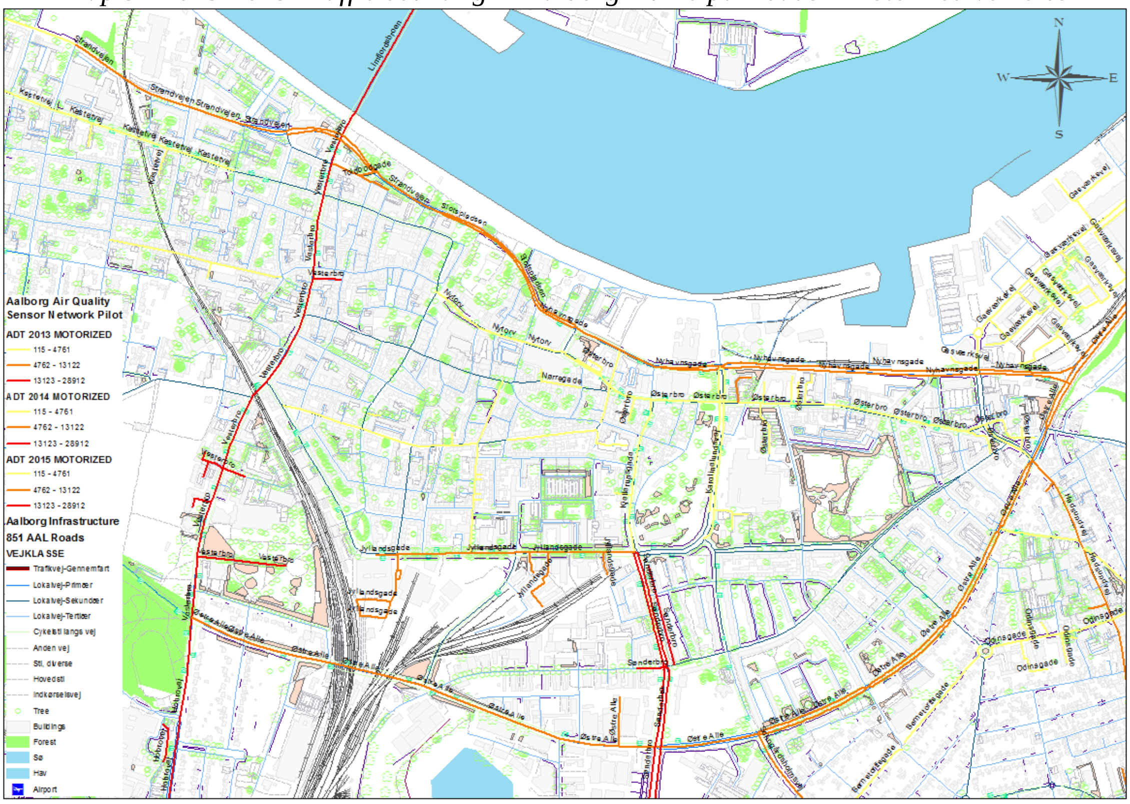
Map 2 - Aalborg largest development areas

4.2.2 Traffic counting analysis on Aalborg municipal roads

Data on traffic counts from 2013 to 2015 was obtained from the opendata.dk portal in an excel format and correlated with the infrastructure shapefile through their administrative road number for analysis. The datasheet is quite extensive and presents information about speed patterns of traffic, day and night peak hours and specification on the counting. Concerning traffic, data is calculated and presented for Annual Daily Traffic (ADT), July Hour Traffic (JDT), and Everyday Hour Traffic (HDT).

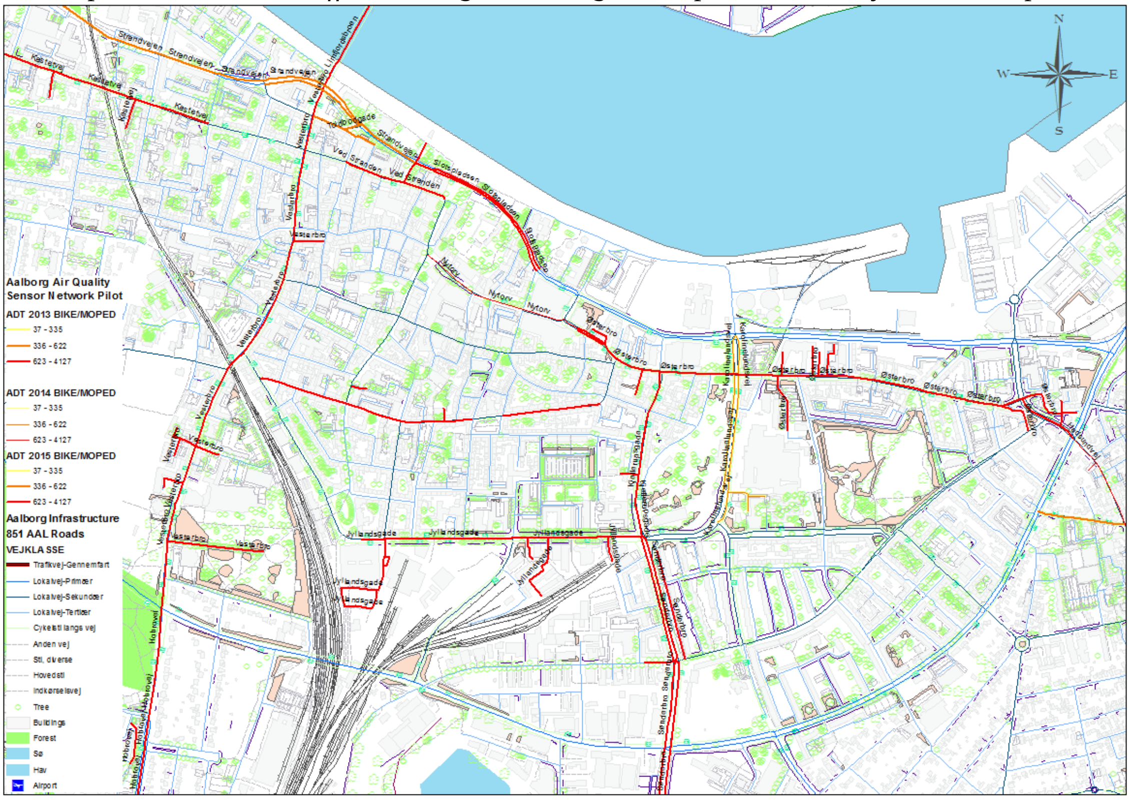
For this research purpose, the ADT traffic calculated as the average 24 hour traffic throughout the year was selected in order to identify traffic hotspots in the urban area. The traffic is identified by M, K or C for motor vehicles, moped and bikes correspondingly. It is important to note that some data was disregarded due to incompatibility factors or unpolished data. The following maps (Map3 and Map4) depict the analysis described, for motorized vehicles (M) and bicycles/mopeds (K, C) respectively.

Map 3 - 2013-2015 Traffic counting in Aalborg municipal roads – motorized vehicles



Source: (Erhvervsstyrelsen, 2018; ESRI, 2016; OIS, 2018; Open Data DK, 2015; Styrelsen for Dataforsyning og Effektivisering, 2018)

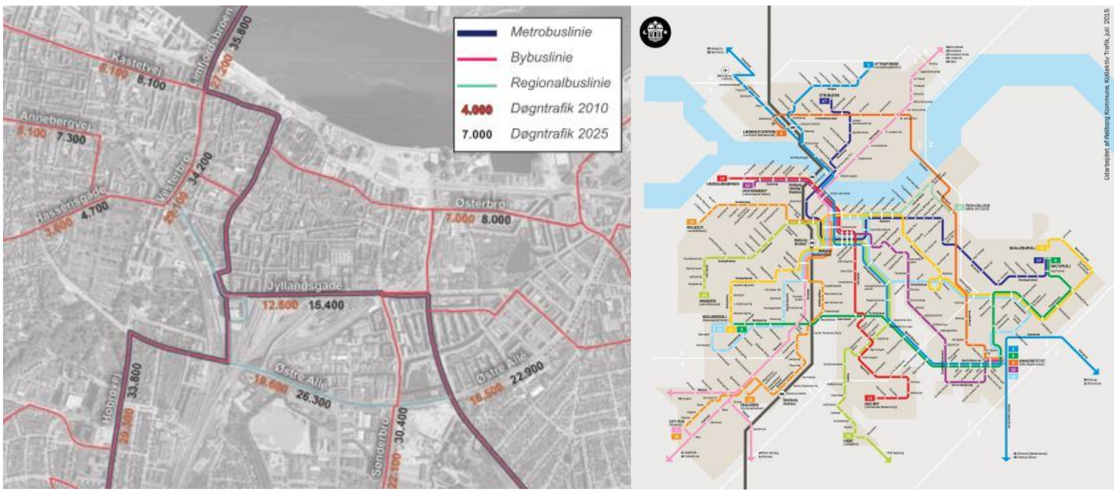
Map 4 - 2013-2015 Traffic counting in Aalborg municipal roads – bicycles and mopeds



Source: (Erhvervsstyrelsen, 2018; ESRI, 2016; OIS, 2018; Open Data DK, 2015; Styrelsen for Dataforsyning og Effektivisering, 2018)

Public transportation plays a principal role in Aalborg's traffic. Current bus routes and future traffic model calculations for 2025 are shown in the maps below. The map on the left emphasizes the expected increase in traffic for the following years along Aalborg's principal corridors.

Figure 11 - Current Aalborg public transportation and 2025 projected traffic

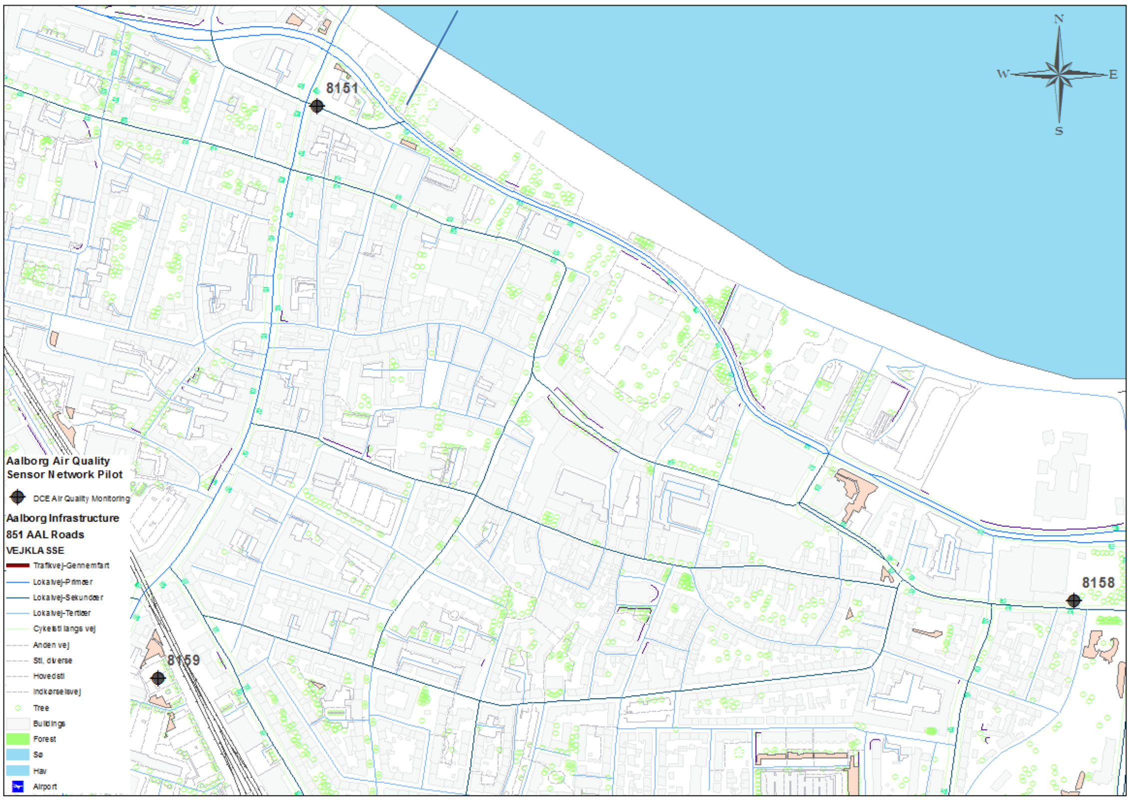


Source: (M. Jensen et al., 2015)

4.2.3 Current Aalborg official monitoring stations

The Danish Air Quality Monitoring Programme allocates official mesurement stations throughout the country. For Aalborg, three street stations are mentioned by the DCE and are shown in Map6. Station 8158/ Østerbro replaced station 8159/ Aalborg Technical Administration from 2004 according to their webpage. Additionally, station 8151/Vestebro is temporarily closed due to construction and it is projected to be relocated in the early future.

Map 5 - Danish Air Quality Monitoring stations in Aalborg

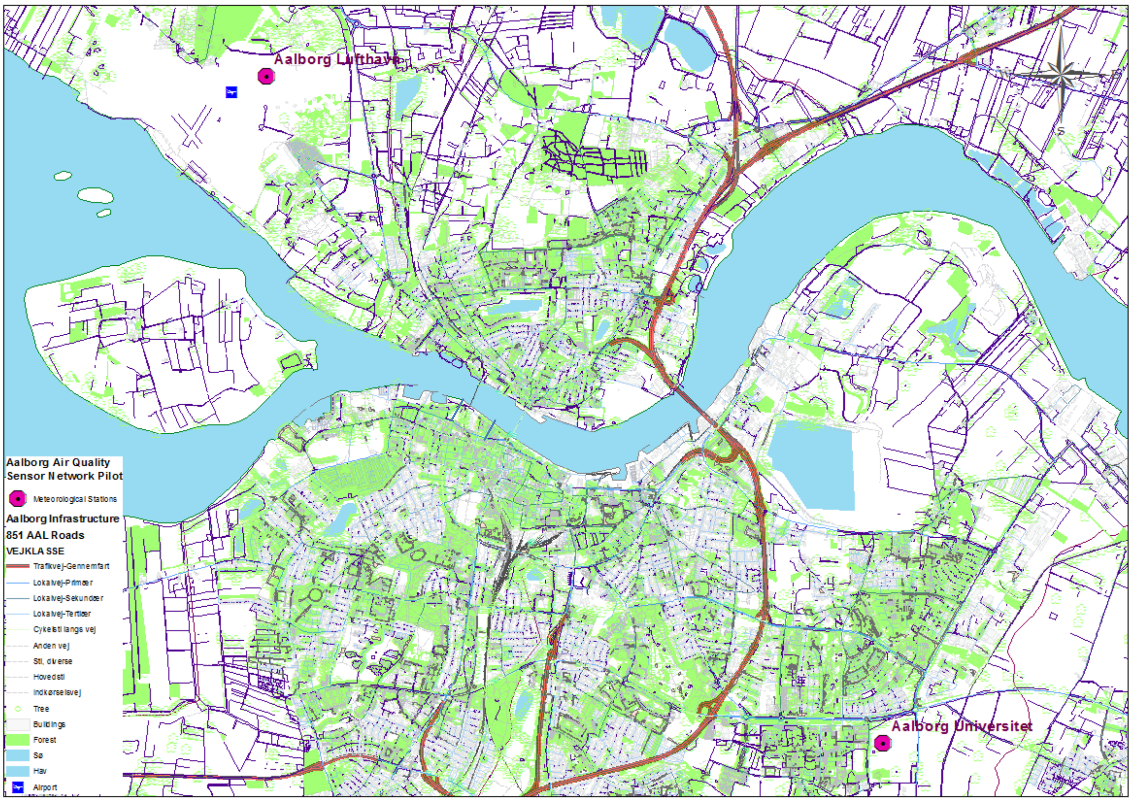


Source: (Ellermann et al., 2017a; Erhvervsstyrelsen, 2018; ESRI, 2016; OIS, 2018; Open Data DK, 2015; Styrelsen for Dataforsyning og Effektivisering, 2018)

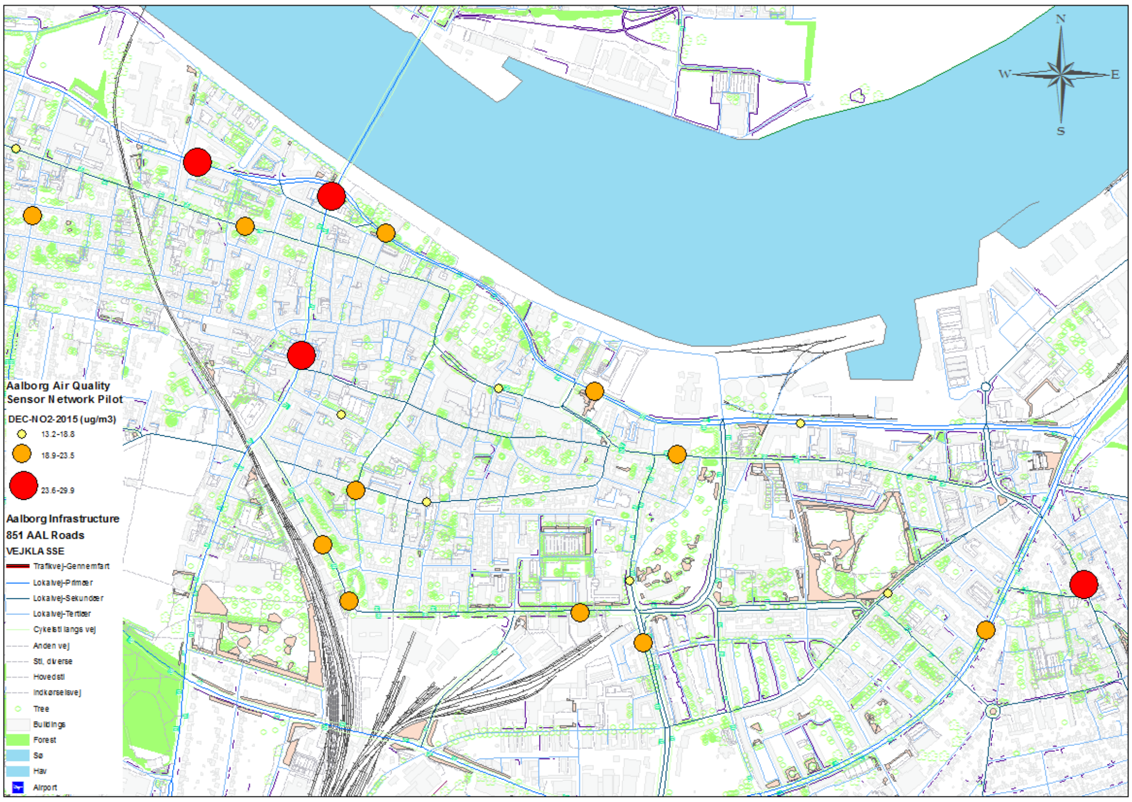
Estimated locations of meteorological stations close to the urban area of Aalborg are shown in Map7. It is worth mentioning that the locations of these meteorological stations have been confirmed through online content and it's not certified by any official entity report or resource.

Additionally, the 2015's data for Nitrogen Dioxide (NO_2) concentrations modeled by the DCE are additionally presented in Map8. The data is available through the Web Map Services at ESRI's portal. Sizes of the bubbles are proportional to the gas concentration.

Map 6 - Aalborg Meteorological stations



Map 7 - 2015 NO2 concentrations in urban Aalborg



Source: (DCE, 2015; Ellermann et al., 2017a; Erhvervsstyrelsen, 2018; ESRI, 2016; OIS, 2018; Open Data DK, 2015; Styrelsen for Dataforsyning og Effektivisering, 2018)

5. In situ Observations and Interviews

Different hotspots throughout the city were visited and observations were made. Kastetvej in Vestby, the transition from Vestebro to Hobrovej, Jyllandsgade from the Aalborg busterminal to the Police Station, Ostebro 7 close to the DCE monitoring station, the transition from Kjellerupsgade into Sønderbro, and Handsundvej in Vejgaard. Infrastructure and traffic in different times of the day during weekdays and weekends were observed in order to analyze patterns and agglomeration zones.

From the interviews taken place some important information about the Danish Air Quality Monitoring Programme and the traffic monitoring in the city of Aalborg was obtained.

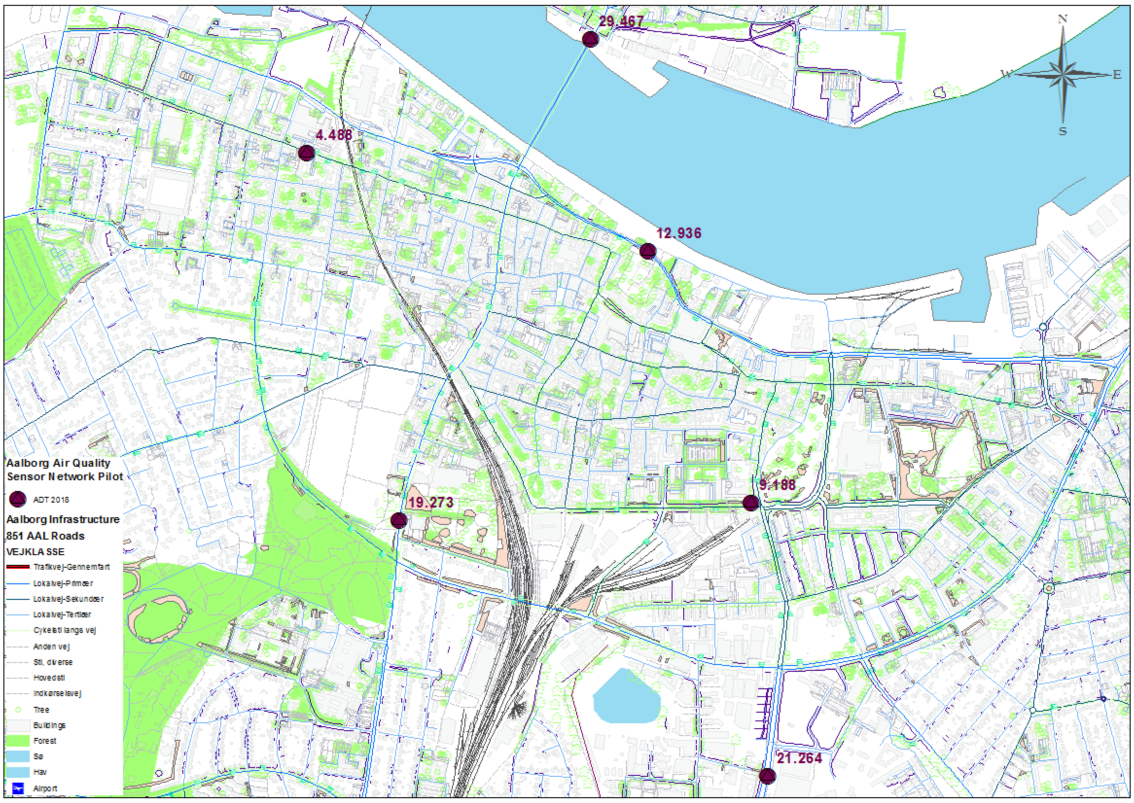
Thomas Ellermann, senior researcher working at the Department of Environmental Sciences at Aarhus University was consulted by phone. Ellermann clarified and confirmed the current status of the Aalborg official AQ stations. Currently, only station identified as 8158, located in the rooftop of Østerbro 7 is operating. Automatic instruments feeding the open available data of the DCE correspond to Nitrogen Oxides (NO_x and NO_2) and Ozone (O_3). Particulate Matter is measured by samples taken to the laboratory and therefore data cannot be obtained in real-time and will take up to 2 months to be released. Ellermann mentioned that the data available online is raw and has not been depurated in any way.

It was said that the meteorological station the DCE uses for Aalborg is located approximately 1 km south of Aalborg, regardless, its exact location was not provided.

During the consultation, the researcher emphasized on the high accuracy of measurement from official fixed stations due to the assiduous and certified calibration the instruments undergo – by the DCE personnel - at the beginning of each month. The possibility of coordination for the installation of the sensors allocated for this research in the surroundings of the fixed official station was discussed. When asked to provide some recommendations for this pilot project, Ellermann recommended allocating the sensors in the public infrastructure. Regarding the height and place of installation, it was recommended to use light poles and 3.50 meters height to prevent any type of possible vandalism to the instruments. At the same time, the senior researcher and head of section attested the challenges of using low cost AQ sensors for AQ monitoring, reveling previous unfortunate experiences with the data quality and instability of similar devices.

Anders Yde-Nielsen is a master student from the Department of Civil Engineering at Aalborg University, interning for the Traffic & Roads Department at Aalborg Municipality. Yde-Nielsen provided important insights on the current traffic monitoring of the city. A variety of sensors are allocated throughout the city both permanently and temporarily, six permanent monitoring stations were spotted due to the potential importance for this research and are depicted in the map below with their correspondent averaged ADT for 2018. Mixed counting stations and only cyclist counting can be found in different spots of the city. The monitoring stations feed an extensive database in which data can be filtered, exported and downloaded tailored to any convenience. The counters differentiate traffic in automobiles and bicycles, automobiles being further classified as automobile, SUV or lorry accordingly. The data when required can be polished and cleaned in approximately 2 weeks after required. Any type of pedestrian counting is not available at the moment. It was also stated that the time lapse between counting is 30 minutes; nevertheless, the station on Jylllandsgade between Dag Hammerskjölds Gade and Sønderbro provides 15 minute counting. Map9 illustrates the geographical distribution of the traffic monitoring stations in Aalborg.

Map 8 - Official permanent traffic monitoring stations in Aalborg



Source: (Erhvervsstyrelsen, 2018; ESRI, 2016; OIS, 2018; Open Data DK, 2015; Styrelsen for Dataforsyning og Effektivisering, 2018)

6. Results

6.1 Low cost Air Quality Sensor Network deployment in Aalborg city

6.1.1 Sensor location

After performing the correspondent geographical analysis of Aalborg's urban area, some key characteristics are found for the sensor geographical location and distribution. The idea behind the analysis is to not only identify possible hotspots in the city but also further analysis with other city infrastructure and monitoring stations. The following will develop better this last notion:

- Air pollution sources: Aalborg's land's use urban area is mainly composed by residential and commercial areas. By now, industry has almost entirely moved its installations to the outskirts of the city. Certain constructions/renovations are spotted in localized buildings, mainly located in development areas within the urban zone.

  The traffic data obtained and geo-visualized was used to identify the most congested routes within the urban Aalborg. Annual Daily Traffic (ADT) provided a certain insight into traffic mobilization from and to the urban area. By one hand Vestebro and Sønderbro are important corridors for traffic coming from south to Aalborg Centrum besides the obvious communication with Norresundy. Kastetvej and Handsundvej on the other hand communicate Vestby and Handsundby to the centrum respectively and so vice versa.

  The dataset obtained provided some insight on active mobility traffic for bicycles and mopeds and therefore human exposure could somehow be analyzed. Residential areas and commercial pedestrian areas were also taken into account. However, pedestrian counting is not performed by the municipality due to the complexity of its nature. Subsequently, this research was not able to include this parameter into its assessment.

  Public transportation plays an important role in urban outdoor air pollution. The city bus routes were also taken into account and the combination of Metrobusline and Bybusline made Jyllandsgade road of an importance interest for the location of the sensors.

  The permanent traffic monitoring locations of Aalborg Municipality are envisioning strategic areas in which insights of air pollution and vehicle emission can be correlated. Therefore, these played a decisive role for the sensors allocation.

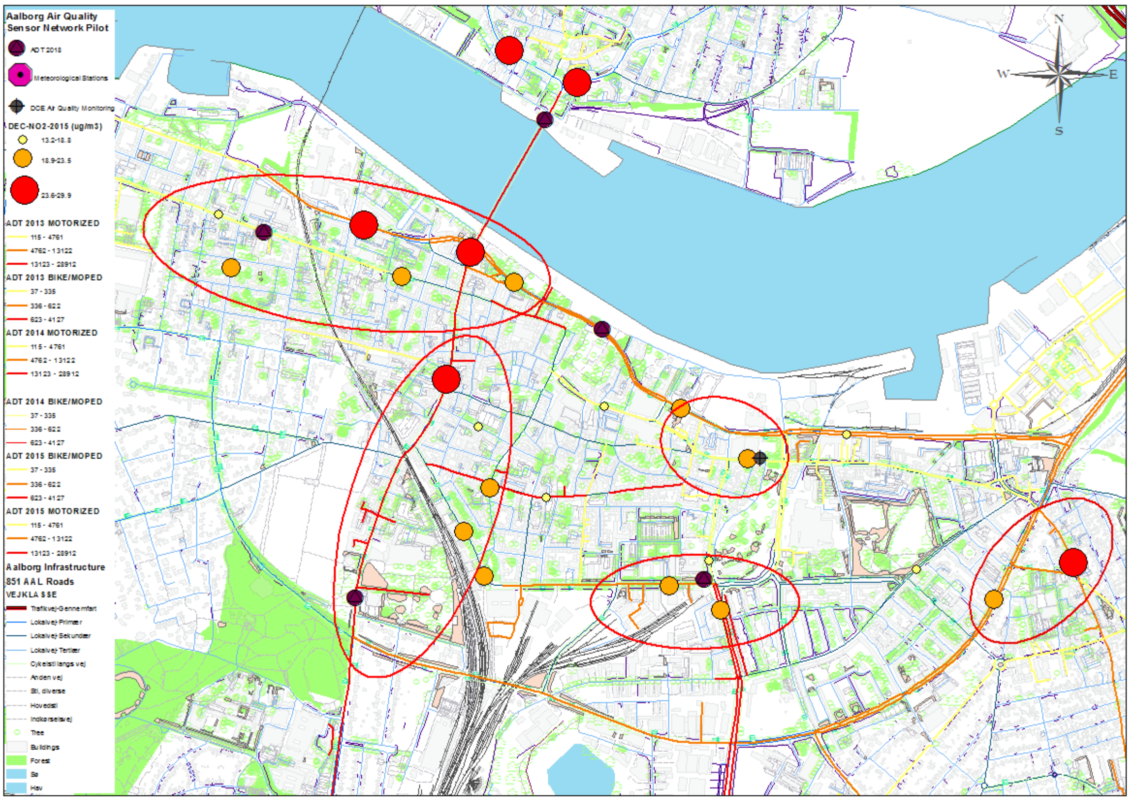
- Official air quality monitoring stations: The official AQ monitoring station found in Østerbro represents an important control point for the assessment of the data quality of the sensors. The relation between measurements will provide understandings in the sensor's data precision.

- ➢ <u>Official meteorological monitoring stations:</u> Meteorological parameters have the potentials of accentuate or exacerbate chemical reactions of pollutants in the atmosphere. Meteorological parameters from official stations were advisable for data quality purposes. Their expected yet not confirmed official locations did not play a main role in the location of the sensors. Unfortunately, wind speed and direction monitoring station locations were not obtained; regardless, their importance is remarked.

- ➢ <u>Official reports:</u> As advised previously, Nitrogen Dioxide (NO_2) concentrations of the DCE from 2015 were mapped in order to identify the major concentrations hotspots in the city.

Based on these parameters, areas of significance for urban outdoor AQ and human exposure were spotted and accordingly signalized in the following map.

Map 9 - Hotspot identification in Aalborg urban area

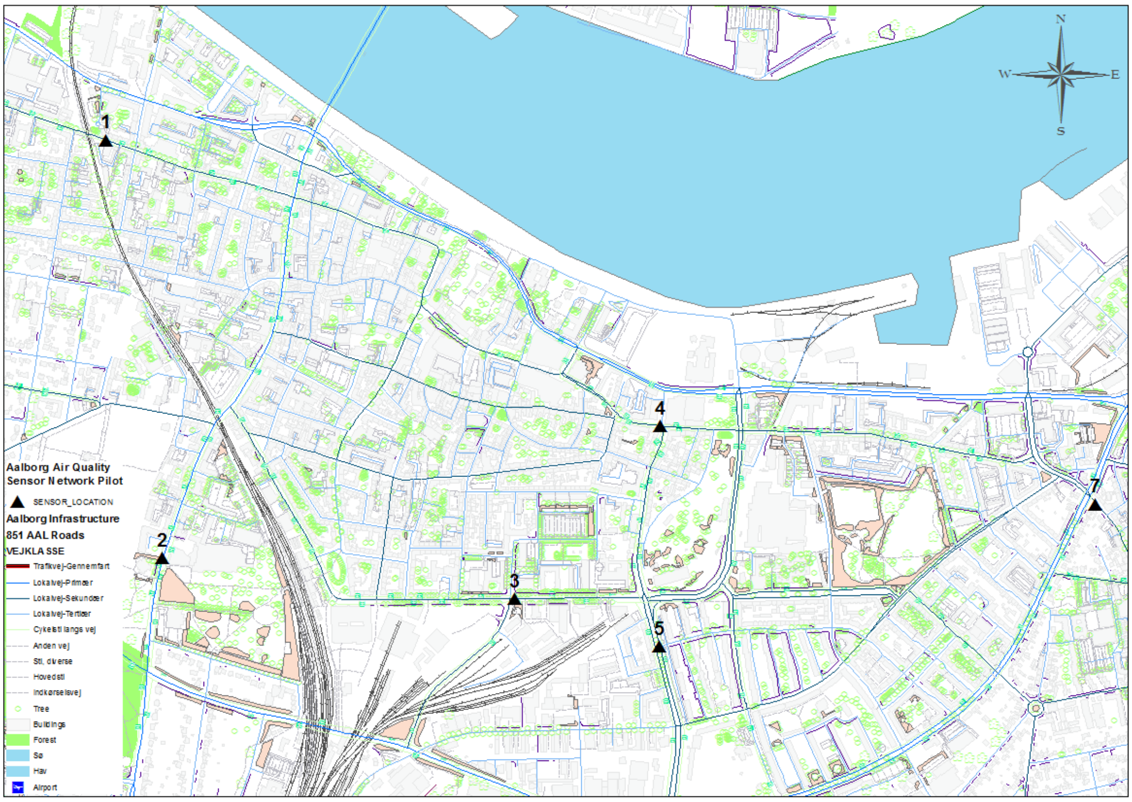


Source: (Erhvervsstyrelsen, 2018; ESRI, 2016; OIS, 2018; Open Data DK, 2015; Styrelsen for Dataforsyning og Effektivisering, 2018)

Based on these areas circled by red ellipses, the allocations of the available sensors were assigned accordingly. Another aspect here is to mention that 6 of the 7 available sets of sensors are to be allocated in Aalborg urban area. The other available sensor is determined to be mobile and versatile to work with further projects which this research aims to enable i.e. sensors mounted to a drone to assess its usability for AQ monitoring.

A meeting was held with one of the representatives of Aalborg Municipality for the presentation of this research project along with its expected outcomes and potentials. Right after, during the timeline of this research a formal proposal of the sensors locations was presented to the Aalborg Municipality. The previous was made in order to obtain approval of the addition of the sensors into the city's infrastructure. On the first proposal, the attachment of sensors to traffic lights, public antennas serving as public lighting support, and buildings facades was contemplated. Regardless, it was advised by the municipality to only use light poles whose height equal or exceed seven meters. The height of installation of the sensors was approved to be from 3.50-4.00 meters. The locations are geographically illustrated in the following map:

Map 10 – Location and distribution of Aalborg LCAQMSN Pilot



Source: (Erhvervsstyrelsen, 2018; ESRI, 2016; OIS, 2018; Open Data DK, 2015; Styrelsen for Dataforsyning og Effektivisering, 2018)

The following tables depict the locations proposed environment through a panoramic view. The description of each of the locations is presented on the following page:

Table 8 – Panoramic view of the proposed locations of Aalborg LCAQSN

N°	Street name and view
	Kastetvej/Kastetvej
1	
	Vestebro/ Europa Plads
2	
	Jyllandsgade/Dag Hammarskjølds Gade
3	
	Østerbro/Kjelleryps Torv
4	
	Sønderbro/Færøgade
5	
	Handsundvej/Østre Alle
7	

Table 9 - Description of the proposed locations for Aalborg LCAQSN				
	Zone		**Infrastructure**	
Location	**Type**	**Background**	**Type**	**Height [m]**
1	Residential	Urban	Public light pole	3.5-4.0
2	Traffic impacted	Urban		
3	Traffic impacted	Urban/Centrum		
4	Residential	Urban/Centrum		
5	Traffic impacted	Urban		
7	Traffic impacted	Urban		

6.1.2 Sensor programming

The Libelium Smart Environment PRO WASPMOTE Plug & Sense series sensors were programmed manually through the Libelium IDE for Waspmote (Waspmote IDE). The platform uses its own programming language and also allows to manage C and C++coding files. Libelium offers open code source along with examples on their webpage and almost instant support for developers on its forum. Code is also openly available in a Libelium GitHub Code Repository. The programming structure responds to 3 main sections which are detailed in the figure below:

Figure 12 - IDE coding structure

```
// 1. Include Libraries
// 2. Definitions
// 3. Global variables declaration
```

Unique declaration of variables

```
void setup()
{
   // 4. Modules initialization
}
```

Function running only once and initializing the Waspmote

```
void loop()
{
   // 5. Measure
   // 6. Send information
   // 7. Sleep Waspmote
}
```

Infinite loop function running continuously according to the time lapse in between measurements programmed

Source: (Libelium, 2017c)

The coding for the sensors establishes 4G radio communication through the embedded SIM card allowing access to internet. It proceeds with the setting of operator parameters (Access Point Name, login and password), 4G module Activation, e-mail parameters (receiver and sender), Simple Mail Transfer Protocol (SMTP) server parameters (security and port) and finally the association of each probe to the correspondent socket. Each sensor is associated with specific designed sockets which are described in the following table:

Table 10 - Allocation of sensors by socket

ON Power consumptio n	Reading Parameter	Unit	Sensor Name	Socke t
2 µA	Temperature	ºC	Temperature, humidity and pressure probe	E
2.8 µA	Humidity	% RH		
4.2 µA	Pressure	Pa		
312 µA	CO	ppm	Carbon Monoxide (CO) for low concentrations [Calibrated] Probe	C
85 mA	CO2	ppm	Carbon Dioxide (CO2) [Calibrated] Probe	F
<1 mA	NO2	ppm	Nitric Dioxide (NO2) [Calibrated] high accuracy Probe	B
<1 mA	SO2	ppm	Sulfur Dioxide (SO2) [Calibrated] high accuracy Probe	A
260 mA @ 5 V	PM1/PM2.5/PM1 0	µg/m3	Particle Matter (PM1/PM2.5/PM10) – Dust Probe	D

Source: (Libelium, 2017a)

After initializing the sensor board and each gas probe, the sensors are sent to a three minute warm up time which is highly recommended by the manufacturer in order to acquire the best data quality possible. As seen in the table above, each sensor has different current consumption (Particle Matter being the most energy intense) and therefore, the sensors are sent to sleep in between readings. Measurements are performed on fifteen minute intervals and sensors wake up through an alarm included in the coding. Following performing each measurement, the device is programmed to create a frame containing information of the readings and send it in an American Standard Code for Information Interchange (ASCII) format to the email provided which structure is shown in the following image. The complete code is attached in Annexes.

Figure 13 - ASCII frame structure

HEADER										PAYLOAD							
<=>	Frame Type	Num Fields	#	Serial ID	#	Waspmote ID	#	Sequence	#	Sensor_1	#	Sensor_2	#	...	Sensor_n	#	

Source: (Libelium, 2013)

This communication methodology was chosen due to the 4G module embedded on the sensors and the - at the time - unavailability of devices needed to reach a more efficient and less manual process for data acquisition.

6.1.3 Sensors structure

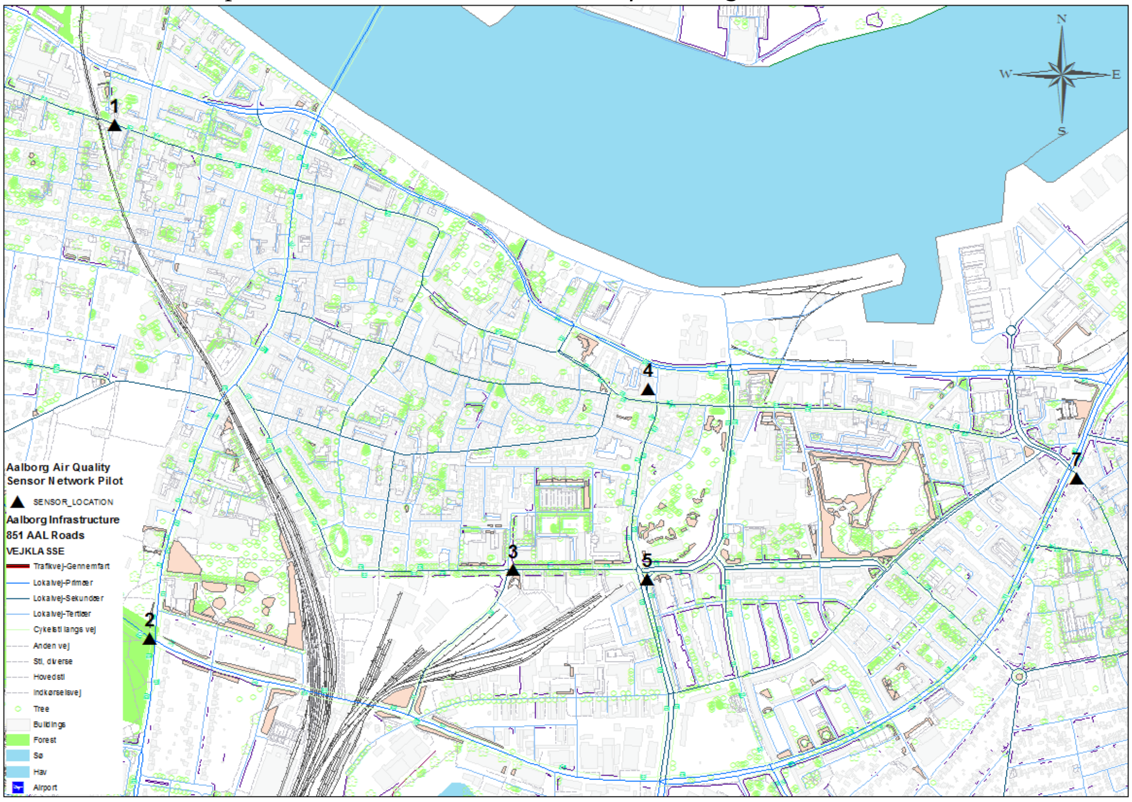
In order for the complete set of sensors to be installed in public lighting poles in a safe manner, it was decided to mount all the components in a single A3 sized aluminium plate. This structure was used in the Carbon Track and Trace 2.0 mentioned in 3.1 for the cities of Trondheim and Vejle. The plate is to be attached to the poles through steel bars that will secure the structure to the light poles. The structure can be seen in the following pictures:

Figure 14 - Sensors structure

6.1.4 Installed sensors

In the field, some difficulties were found regarding the steel bar dimensions and the difference of diameters in the proposed poles. However, alternative poles in the vicinity according to the approved locations were selected for location 2 and 5. For location 4, the opportunity to allocate the sensors on the hut were the DCE official monitoring station operates was chosen for control purposes. Locations 1, 3, and 7 did not suffer any change. The following map describes the final geospatial sensor allocation and distribution:

Map 11 – Location and distribution of Aalborg LCAQMSN Pilot



Source: (Erhvervsstyrelsen, 2018; ESRI, 2016; OIS, 2018; Open Data DK, 2015; Styrelsen for Dataforsyning og Effektivisering, 2018)

Tables 11 and 12 depict the locations proposed along with its exact coordinates and the pictures of their installation.

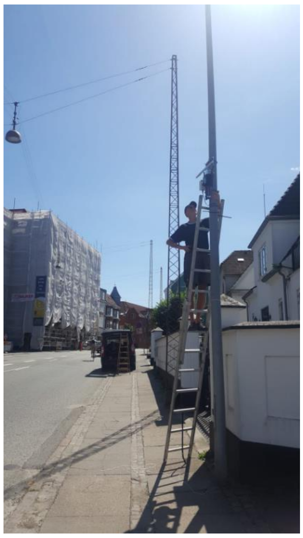
Table 11 - Description of the installed locations for Aalborg LCAQSN

	Zone		**Infrastructure**		**Coordinates**	
Location	**Type**	**Background**	**Type**	**Height [m]**	**X [UTM32]**	**Y [UTM32]**
1	Residential	Urban	PLP[1]	3.5	555161	6323605
2	Traffic impacted	Urban	PLP[1]	3.5	555249	6322325
3	Traffic impacted	Urban/Centrum	PLP[1]	3.5	556152	6322495
4	Residential	Urban/Centrum	Private	7.5-8.0	556488	6322947
5	Traffic impacted	Urban	PLP[1]	3.5	556487	6322472
7	Traffic impacted	Urban	PLP[1]	3.5	557558	6322724

[1] Public light pole

Table 12 -Installed LCAQMSN in Aalborg

1	**Kastetvej/Kastetvej**	**2**	**Vestebro/ Kong Christians Alle**	**3**	**Jyllandsgade/Dag Hammarskjølds Gade**
					
4	**Sønderbro/Færøgade**				
					

5	Sønderbro/Fyensgade	7	Handsundvej/Østre Alle
			

6.2 Metrics for smart sustainable development

This section aims to show effective and usable metrics to which this LCAQMSN could support with. The usage of metrics for the assessment of sustainable and smart development have been explained and exposed through literature review and document analysis in this research. The interoperability required between these two frameworks amongst the different city's management spheres has also been pointed out. To demonstrate what has been stated, an example of these correlations is to be made taking the Aalborg municipality mobility's strategy for 2013-2025. The main target of this strategy is to increase modal spilt of sustainable transportation being biking, walking, and public transportation. The specific objectives for the municipality with regards to urban mobility are detailed in the following table.

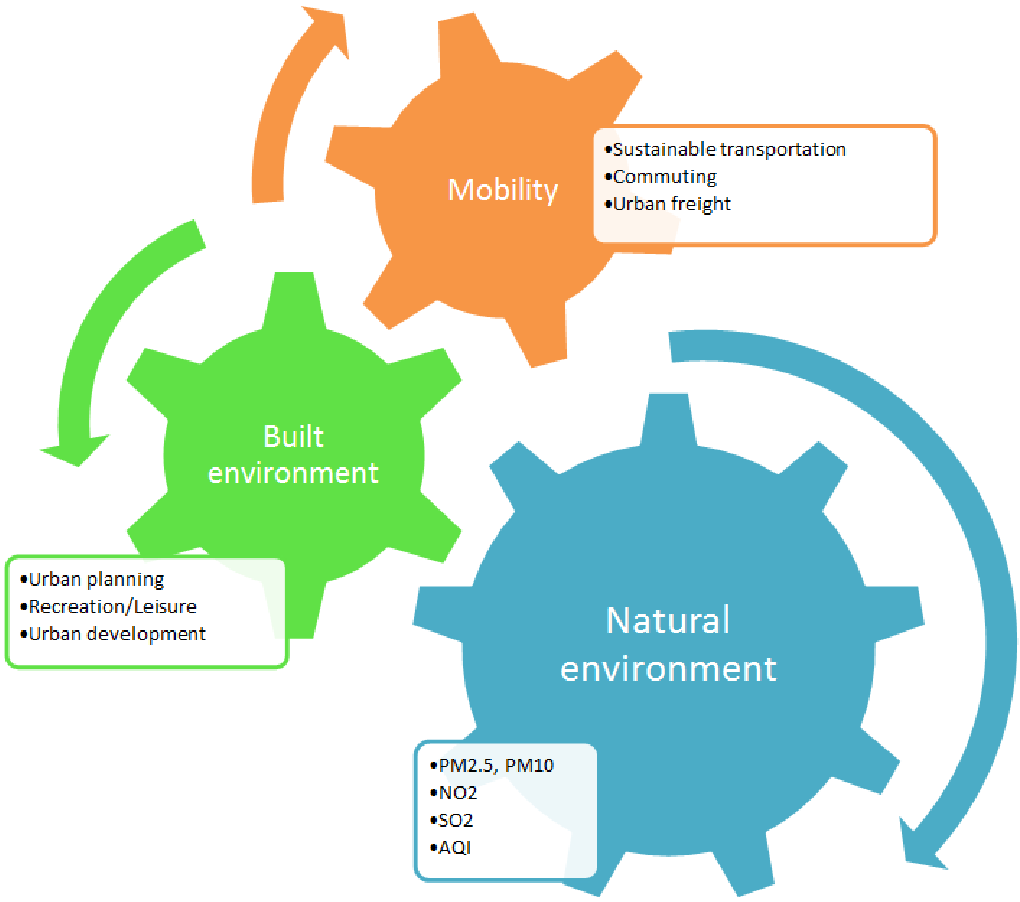
Table 13 - Aalborg Mobility Strategy 2013-2025 objectives

Objectives	Focus
Pedestrians, cyclists and users of public transport must have high priority within the town centre. Urban open spaces should be integrated into areas of transport in order to strengthen urban life. A lower priority should be given to cars passing through the town centre.	Active mobility and public transport as main priority
A high level of accessibility for cyclists in Aalborg must be ensured through the implementation of a high class network of bicycle lanes. The most important connecting bicycle routes will be selected and classified as a primary lane network.	Access to bike lanes for cyclist
A high level of accessibility must be ensured from the town centre to regional and international connections: The University, The University Hospital, The East Harbour and Aalborg Airport.	Development areas transportation accessibility

Transport of goods must be effective, sustainable and help improve the urban environment by reducing air pollution and congestion.	Urban freight
New parking spaces should be restricted to larger parking areas on the outskirts of the town centre.	Urban & transportation planning
Urban densification close to high class public transport should enhance passenger growth and not generate new car journeys.	Urban & transportation planning
Source: (Aalborg Kommune, 2013)	

In an urban setting, transportation and urban planning have a direct influence in the environment. Localized AQ metrics enable the measurability of those impacts at a local level and real-time. The following figure depicts the relationship amongst the relevant categories:

Figure 15 - Interoperability between Natural Environment, Built Environment and Mobility categories in an Urban Area



Additionally, indicators for these categories having direct relation with environmental parameters are presented in the table below. The indicators proposed here are subtracted from the indicator list presented in section 4.1.2.

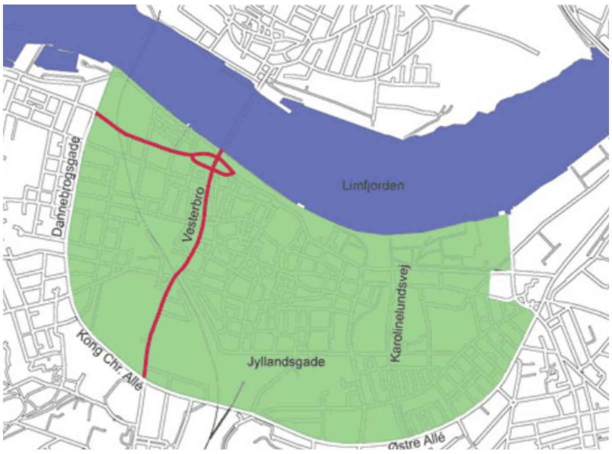
<table>
<tr><th colspan="5">Table 14 - Natural Environment, Built environment and Mobility smart sustainable indicators</th></tr>
<tr><th></th><th colspan="4">Indicators</th></tr>
<tr><th></th><th>Category</th><th>Subcategory</th><th>Name</th><th>Type</th></tr>
<tr><td rowspan="5">Natural Environment</td><td colspan="2" rowspan="4">Environment</td><td>Fine Particulate Matter (PM2.5) concentration</td><td>Core</td></tr>
<tr><td>Particulate Matter (PM10) concentration</td><td>Core</td></tr>
<tr><td>NO2 (nitrogen dioxide) concentration</td><td>Supporting</td></tr>
<tr><td>SO2 (sulfur dioxide) concentration</td><td>Supporting</td></tr>
<tr><td>Planet</td><td>Pollution and waste</td><td>Air quality index</td><td>-</td></tr>
<tr><td rowspan="7">Built environment</td><td colspan="2" rowspan="2">Urban planning</td><td>Green area (hectares) per 100 000 population</td><td>Core</td></tr>
<tr><td>Annual number of trees planted per 100 000 population</td><td>Supporting</td></tr>
<tr><td>People</td><td>Quality of housing and built environment</td><td>Ground floor usage</td><td>City</td></tr>
<tr><td rowspan="3">Planet</td><td rowspan="3">Materials, water and land</td><td>Population density</td><td>City</td></tr>
<tr><td>Brownfield use</td><td>City</td></tr>
<tr><td>Increase in compactness</td><td>Smart project</td></tr>
<tr><td colspan="2">Recreation</td><td>Square meters of public outdoor recreation space per capita</td><td>Supporting</td></tr>
<tr><td rowspan="12">Mobility</td><td colspan="2" rowspan="6">Transportation</td><td>Kilometers of high capacity public transport system per 100 000 population</td><td>Core</td></tr>
<tr><td>Kilometers of light passenger public transport system per 100 000 population</td><td>Core</td></tr>
<tr><td>Annual number of public transport trips per capita</td><td>Core</td></tr>
<tr><td>Percentage of commuters using a travel mode other than a personal vehicle</td><td>Supporting</td></tr>
<tr><td>Kilometers of bicycle paths and lanes per 100 000 population</td><td>Supporting</td></tr>
<tr><td>Transportation fatalities per 100 000 population</td><td>Supporting</td></tr>
<tr><td rowspan="4">People</td><td rowspan="4">Access to other services</td><td>Access to public transport</td><td>City</td></tr>
<tr><td>Access to vehicle sharing solutions for city travel</td><td>City</td></tr>
<tr><td>Access to public amenities</td><td>City</td></tr>
<tr><td>Access to commercial amenities</td><td>City</td></tr>
<tr><td rowspan="2">Prosperity</td><td rowspan="2">Competitiveness and attractiveness</td><td>Congestion</td><td>City</td></tr>
<tr><td>Decreased travel time</td><td>City</td></tr>
<tr><td colspan="5">Source: (Bosch et al., 2016; ISO, 2014)</td></tr>
</table>

The LCAQMSN deployed in the city of Aalborg provides real time measurements and tools for the calculation of all the proposed indicators under the natural environment category. Having this as a control measurement, and taking into account that the hallmark for Aalborg's Mobility Strategy 2013-2025 is to focus in people, different initiatives and measures taken towards the stated objectives can be carefully monitored. Various measures on mobility regarding Aalborg's specific challenges are taken place locally. Route selection, path prioritization, or active mobility exclusive lines are some of the actions currently assessed. These measures intend to reduce public exposure to air pollution while reducing pollution and traffic congestion. The strategy used to promote sustainable transportation is optimizing and improving safety for cyclists by enhancing infrastructure and accessibility to the users. The city aims to become a leading cyclist municipality enhancing the concept of the Danish Bicycle Culture. Parallel efforts are being allocated on public transportation accessibility and infrastructure enhancement with solutions such as the Bus Rapid Transit System (BRT) or the +BUS which will use non-fossil fuel for its operation.

When preference is given to pedestrians, city's often turn to adding infrastructure by implementing traffic lights and crosswalks. Literature suggest that pollutants maintain a steady concentration if traffic has a constant flow. On the contrary, when vehicles stop at intersections or traffic lights, a noticeable higher concentration is distinguished (Aclima, 2018). On one hand, possibly, the projected long-term measure could be resulting in high concentration exposure for crosswalk users. Or, by the other, the pollution exposure window for pedestrians is lower since they are able to cross with a faster route. Now, even if these types of measures pretend to encourage active mobility users while discouraging the usage of private vehicles by segmenting their driving; the impacts on AQ are to be monitored. The indicators calculation shown in the list above could potentially provide accountability on these measures on a certain term but they might as well be useful for decision making on a regular basis.

For example, the Aalborg's environmental zone or commonly referred as "Aalborg's ring" already has some restrictions regarding traffic regulations. This low emission zone (LEZ) is in place since February 2009. Vehicles affected are all diesel-powered above 3.5 tonnes and vans/campervans with 9 plus seats. From November 2011, Euro 3 standard and previous standards have free access with retrofit filter and Danish low emission zone label. Euro 4, 5 and 6 standards have free access with the same label (EU, 2018; Miljøstyrelsen, 2011, 2018a).

Figure 16 - Aalborg LEZ



Miljøzone or LEZ
Roads exempted

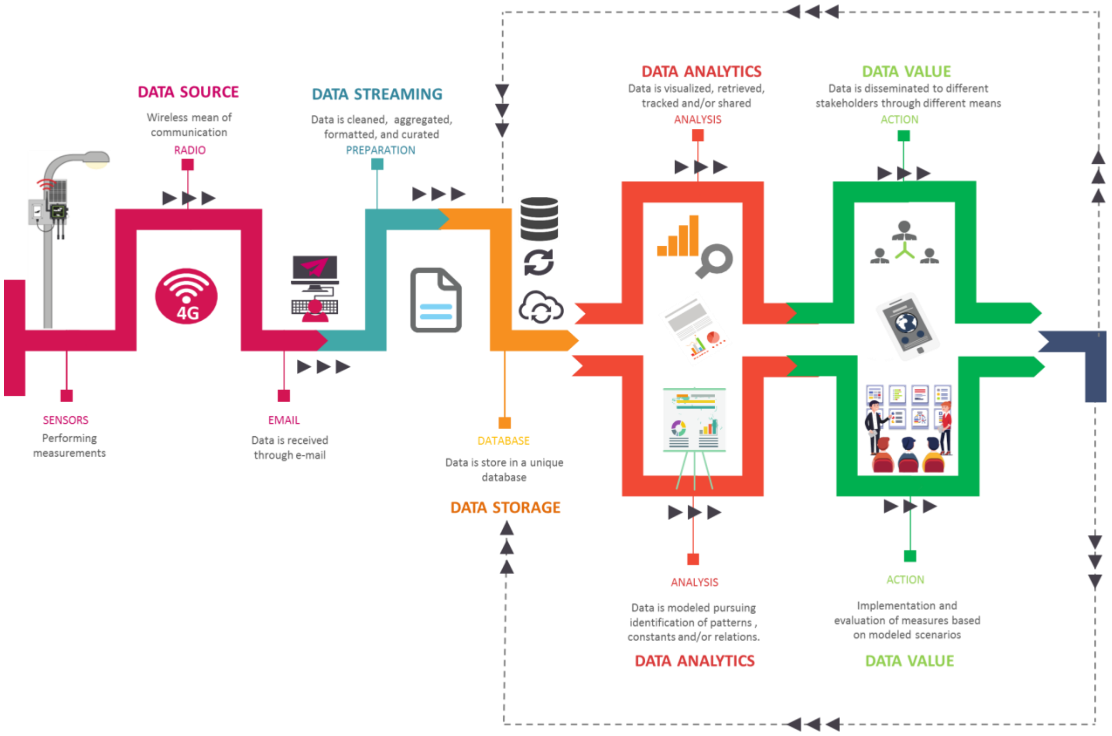
Since the LEZ was established, the vehicles allowed to transit have changed from Euro 3 type to now Euro 4. Heavy duty vehicles like Lorries and commercial trucks have been banned from the zone. In theory, pollutant concentrations inside the polygon should show clear differences with the out of boundaries of the polygon. Local and constant accountability of this type of measurements is important. The differences and variations can be analysed in order to monitor the impact the measure has on outdoor air quality.

From one of the interviews held during the timeline of this research, the Aalborg permanent traffic monitoring stations provide all the necessary insights on traffic data in relatively real-time. If this data is properly correlated and geographically visualized with AQ and other relevant data, pilot measures or modelled scenarios could be monitored, modelled and assessed as needed. Additionally, depending on the final value desired for the sensor network AQ data, users might find the information useful for their decision making at a personal level as well. Whether for deciding a path against another or choosing a certain way of transportation, the final users of these data will have the tools to make their own strategy to reduce their exposure to potential hazardous air pollutants.

6.3 Data value chain

The data value chain for this sensor network has five key phases corresponding to the specific data strategy. In the first step - *Data source* - sensors perform measurements and communicate to the internet wirelessly through 4G network in order to send the data in a frame format. Data is received by a previously designated email for the project and the user is in charge of the next phase – *Data streaming* – which is responsible for the cleaning, aggregation and depuration of the raw data. Clean data is then going to a – *Data storage* – phase in which virtual or physical storage options can be used. Here, the process has a yield in which – depending on the value – data is analysed either on real time or during periods of time through modelling processes in the – *Data analytics* - phase. Here, data is retrieved, tracked, visualized and/or shared in real time or modelled in scenarios based on available models for the assessment of a determined purpose as in human exposure modelling systems. The chain can be visualized in the following figure:

Figure 17- AQ data value chain

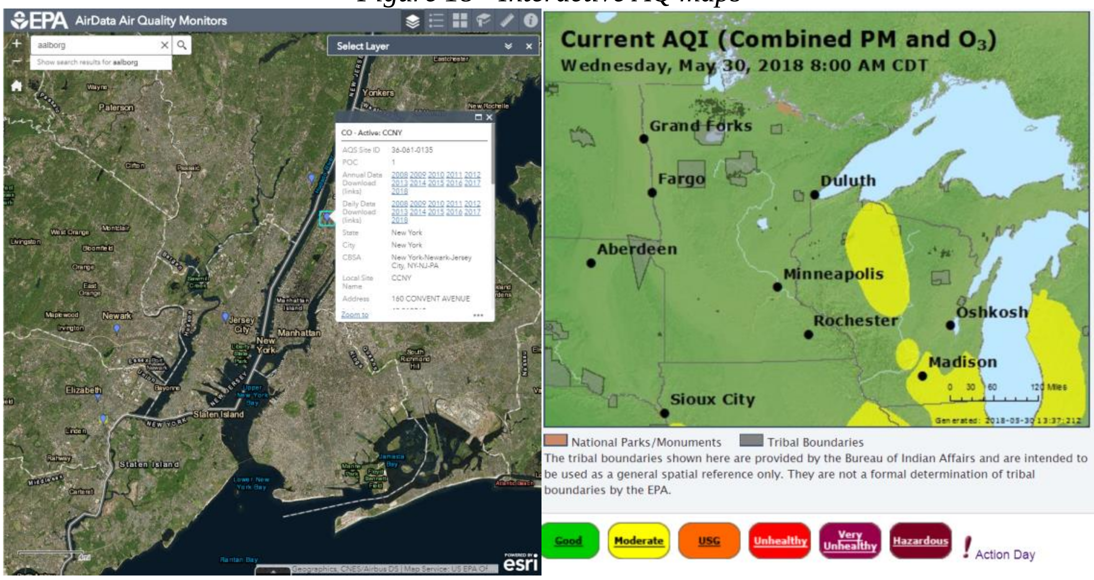


The final phase – *Data Value* – is the decisive phase which determines the final output format of the data and the purpose it will be used for. Here, data is disclosed differently for the specific stakeholder and/or goes to implementation and evaluation of the modelled scenarios if it is the case. The storage phase is being updated in real time since the sensors are continuously operating.

Several methods can be used and have been created for the data analytics phase of this sensor network, some of them are seen in the literature review presented in this research. These include cloud services management, machine learning, or map web services amongst the most commonly used. Here, it is important to identify the target audience which is going to visualize and comprehend the message that is conceived to be sent.

For example, for citizen's awareness on AQ, real time air pollution gases concentration are gathered and calculated as indexes as in the WHO's Air Quality Index (AQI). The index is further translated to visual representations with the usage of scale colours which are geographically located on a map. Users can therefore visualize the data in a self-explanatory format through an interactive AQ map which also allows the retrieval and usage of the open AQ data if needed. On the Carbon Track and Trace 2.0 project a map showing the parameters and current status of the monitoring stations is also available. This allows the user to also identify and familiarize geospatially with the sensors and also with the architecture of the system used to create end-user platforms. As examples, some of the maps are showed below.

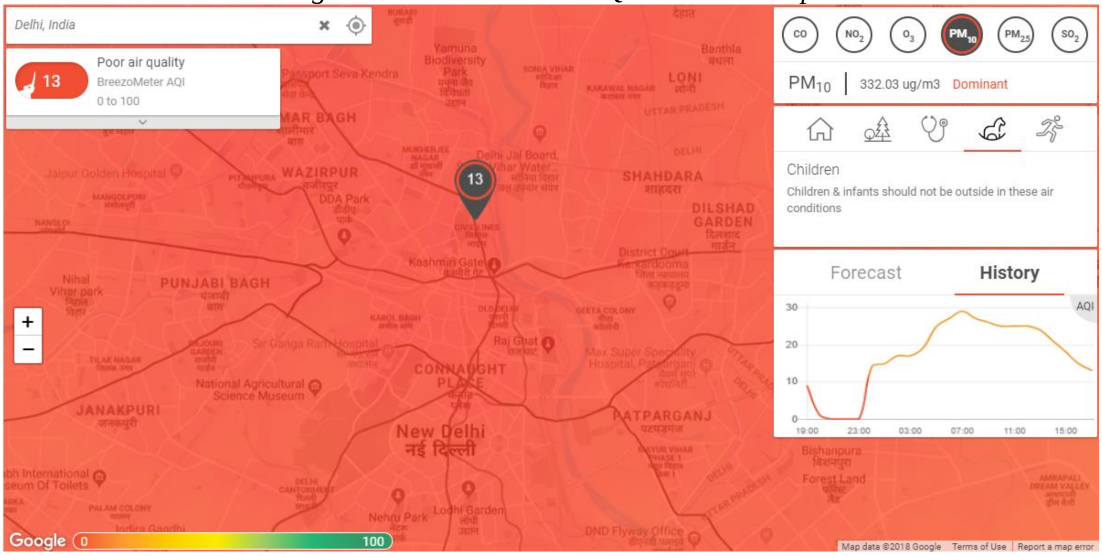
Figure 18 - Interactive AQ maps



Source: (AirNow, 2016; EPA, 2018a)

An interesting case of map usage is BreezoMeter. The company provides real-time, dynamic and location-based data on AQ in order to improve citizen's quality of life. The innovative aspect of their service is that the colour of the AQ index is attached with an intuitive and actionable caption. The caption pretends to advise users about indoor and outdoor activities, health sensitivities, children and sports activities according to the current levels as seen in the figure below. The data can be visualized through web pages or APIs and users can even receive notifications on the level of pollution given a certain location. Alerts can also be sent by notifications, emails or messages.

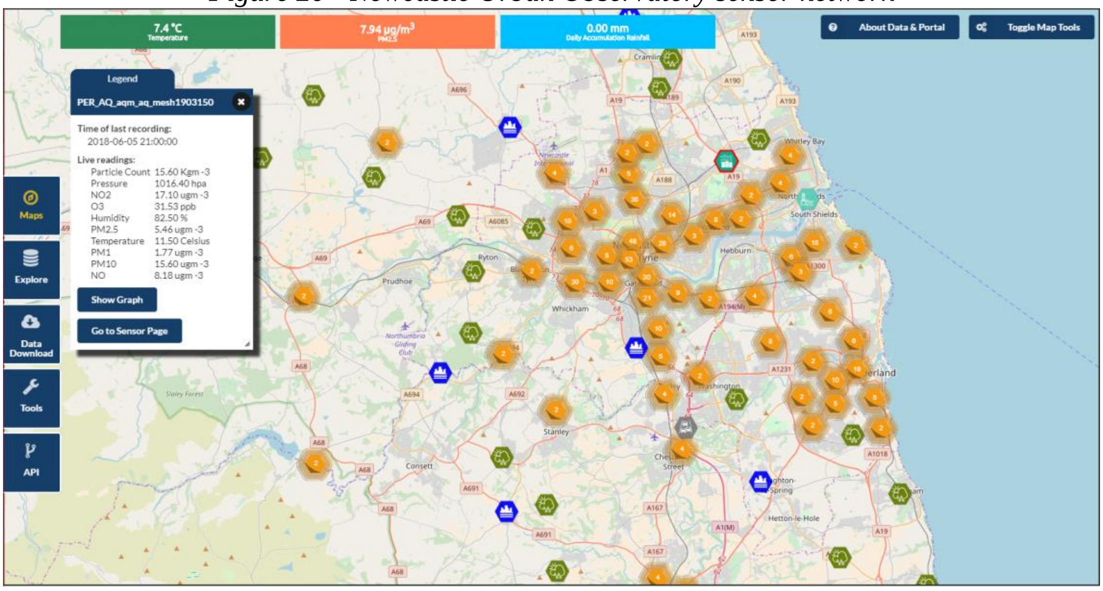
Figure 19 - BreezoMeter AQ interactive map



Source: (BreezoMeter, 2018)

When it comes to sensor deployment and consequently data visualization and retrieval, an imperative case example is the urban observatory of Newcastle in the UK. The data portal of the urban observatory allocates real-time feeds from across the city. The data that can be visualized in a geospatial, graphic or textual form aims to provide a long term baseline for urban research and provide insights into complex urban issues and interfaces (Urban Observatory, 2018). In the following image the extensive network of sensors distributed in the city of Newcastle is shown:

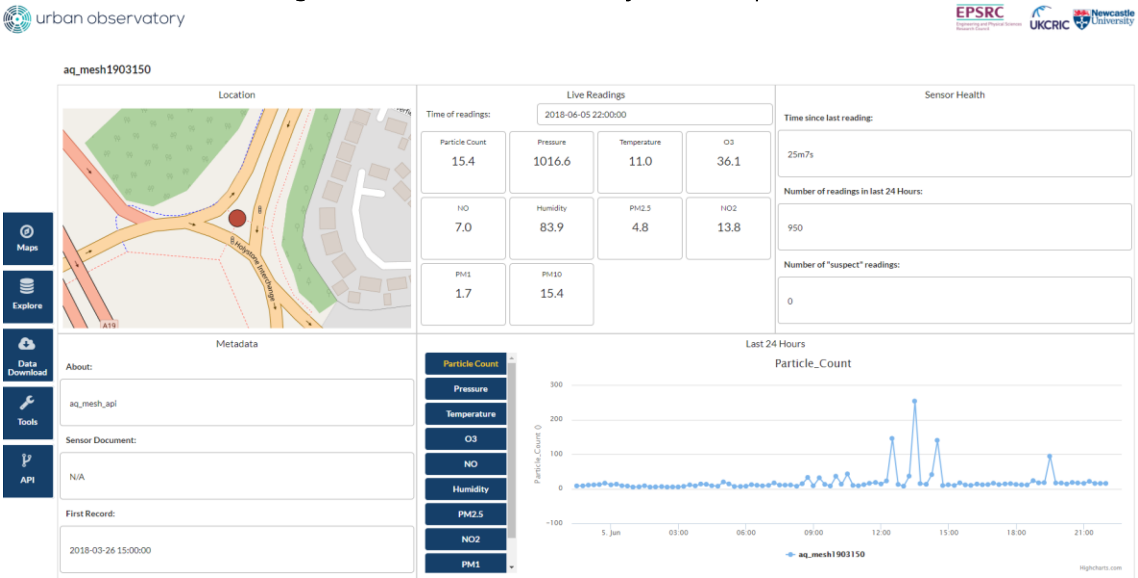
Figure 20 - Newcastle Urban Observatory sensor network



Source: (Urban Observatory, 2018)

Data on traffic, bee hive, environment, air quality, building, weather, electrical, and water level can be visualized and further personalized by parameter for retrieval of open data is available. Each of the sensors allocated a user interface as the one shown in the following figure. Information is also shown on sensor ownerships, current status, maintenance records and sensors issues. An API is also available but requires a previously required key.

Figure 21 - Urban Observatory sensor information

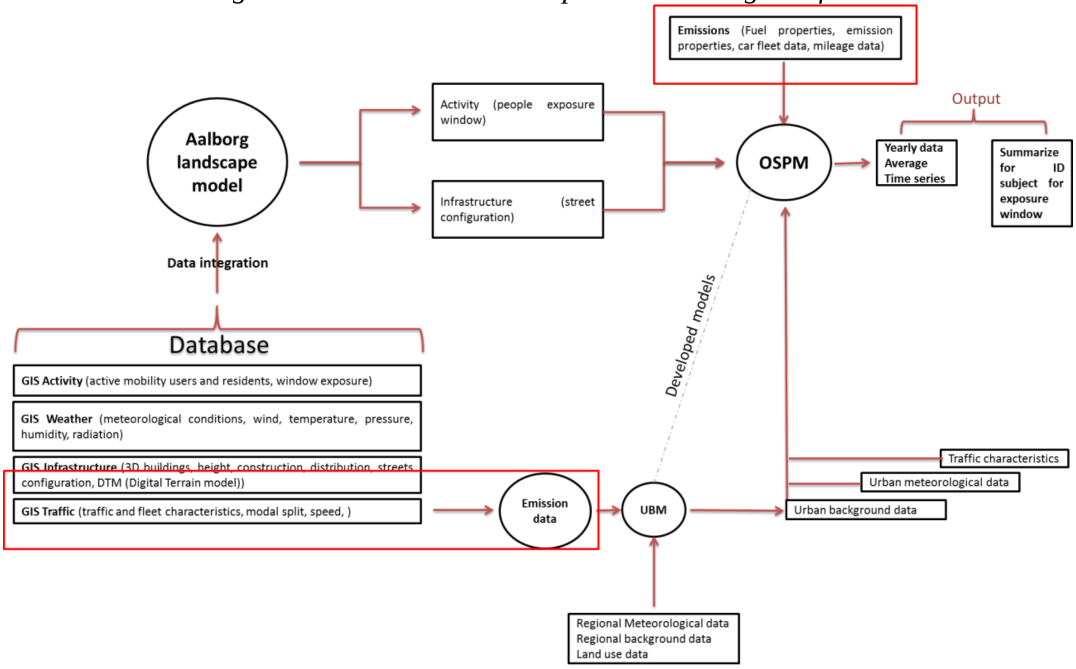


Source: (Urban Observatory, 2018)

New innovative ideas can be implemented without the necessary login of the user into one of these platforms or the use of personal devices. Examples of this could be looking at the city infrastructure, as in street lights signals or interactive screens with AQ colour distinction for an immediate decision making of exposed humans.

Additionally, as seen in the data analytics on the data value chain of this sensor network, the data of a localized AQ network can also support modelling systems usage. As an example for this usage, the Air Quality at Your Street project developed by the DCE is spotted. The AQ in this project was modelled having to input several types of data such as infrastructure, activity, weather, and traffic. The ultimate goal of this system is to illustrate geographical variation of AQ for selected health-related air pollutants. Through the usage of previously developed models as the regional long-range transport model (DEHM), an urban background model (UBM) and a street pollution model (OSPM), the system is designed to have an expected exposure for the residents subject for exposure window. Now, the system requires the input of certain variables and parameters related with emissions and traffic. Real time AQ data has the potential to validate and adjust these variables in order for them to improve prediction and prognostics on a scenario based model. The system can be visualized in the following figure.

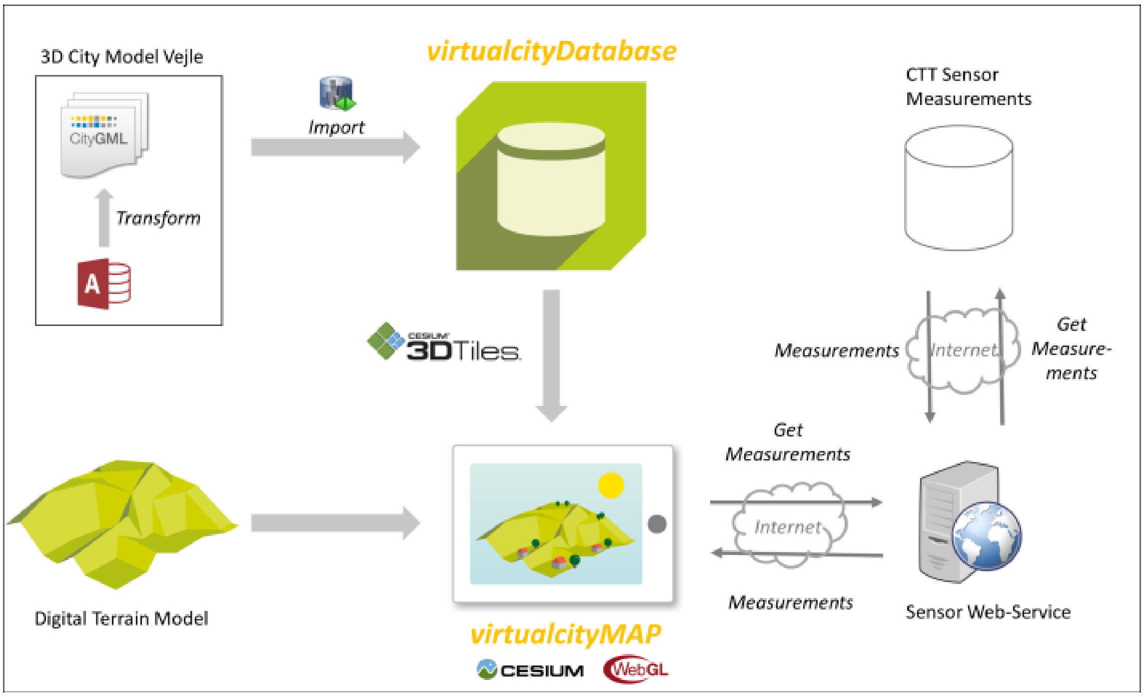
Figure 22 - ArcGIS Human exposure modeling dataflow



Source: (DCE, 2012)

Carbon Track and Trace 2.0 project also integrated the sensor data into a 3D city model for the cities of Vejle and Trondheim. The input data is a digital terrain model (DTM) and a 3D city model. Both databases are needed for the software solution used which is called virtualcitySYSTEMS. The architecture of the prototype can be better understood in the figure below.

Figure 23 - 3D city integrated with AQ sensor data system architecture



Source: (Ross, 2016)

7. Discussion

It is now clear that a smart sustainable city assure efforts into improving quality of life for its inhabitants. People, is always seen as the centre of smart or sustainable development goals. Citizens and authorities have the greatest interests with regards on AQ data. When deciding where to work, live or raise children, AQ is one of the parameters citizens turn to. When decision making comes from a management level, authorities evaluate AQ impacts on the possible measures. From this, monitoring of AQ provides insights of these impacts as part of citizens' rights to environmental information. This discussion is going to be focused in specific matters that this research had as experience and aimed to provide as part of its objectives.

Communication protocol - Regarding the network architecture of this sensor network, the communication via 4G radio and email is certainly not the desired one; even more so if sensors are added to the network. Considerations such as the characteristics of available devices, lack of collaboration of computer sciences specialists and ultimately the timeframe established for this project played a deciding factor when opting for this deployment mechanics. Currently, the data analysis involves the user manually retrieving individual data frames sent via emails to be further converted to a readable format i.e. Coma Separated Values (.csv) format. Therefore, the data value chain proposed for this pilot has proven not to be efficient and neither to have any automation. Libelium's ready to use kit includes the Meshlium gateway and Programming Cloud Services (PCS), offering instant data programming, visualization and management. However, the costs of the device and its license can be considered as a large investment.

For future work of this sensor network, the acquisition of a gateway to reach proper wireless and efficient communication, and likewise the usage of an IoT platform is highly encouraged i.e. free cost IoT platforms as ThingSpeak have been used with Libelium devices, according to literature. Data streaming and data storage are the basis for data analytics and therefore of extreme importance when handling large datasets.

Data accuracy – The controversy of data quality and low cost AQ sensors has been explained through literature review. It is stated by the sensors manufacturer that gases need time to stabilize and therefore measurements should be taken into account after minutes or maybe hours after being installed. Besides, accuracy depends on electrochemical sensors sensitivity. Experience has shown that the lower the pollutant concentration, the reduced the accuracy of the sensor. This matter also denotes the importance of the comparison between sensor data and AQ data from official stations and therefore the allocation of sensor N°4. Furthermore, the level of precision desired is directly linked to the data value determined for a specific usage. For example, decision making and citizen awareness would need different types of data accuracy due to the relevance of the data in the first place. Citizen awareness involves the calculation of an AQ index which averages pollutants concentrations while decision making might be based on scenario modelling needed accurate parameters. It is important to note that the concentrations tendencies and fluctuations provide a good insight on AQ and that is the real value pursued by these types of deployments.

Collaboration – Smart initiatives involve a wide array of interdisciplinary fields on the way. It is important that experts and related stakeholders are identified along with its commitment to collaboration to a certain smart project. The term “Smart” along with the “Smart city” concept has been elaborated through literature review in this report. The interoperability needed for a city to be smart has to be reflected in the human resources allocated for that specific project as well. For example, computer sciences and air quality experts can provide the necessary input for an initiative to acquire its best potential and serve for the specific purpose it is intended to. On the other hand, a solid team has the potential to test and challenge technology through research, what is seen as a necessary process for technology optimization. Therefore, collaboration of an interdisciplinary team is highly encouraged for future work.

From this deployment, experiences evidence the necessary planning and involvement of related stakeholders from the very beginning or even before the starting point of the project. Even when contact was reached, Aalborg Municipality’s permission approval for the sensor locations took much longer than expected which triggered the delay on sensors installation and further data acquisition. This, along with the unsuccessful involvement with Smart Aalborg management stated in methodology, denote a certain misleading operability and unclear leadership on these type of initiatives.

At the same time though, the use cases presented in this research aim to provide examples not only of current sensor networks deployed in other cities but also their efforts towards smartization. This should be taken as an encouraging factor for the city of Aalborg in order to advance with concrete and tangible efforts.

The documentation available on cities smart strategies detail frameworks outlining priorities and actions necessary for transition. The frameworks emphasize on the principal role played by collaboration, connectivity, efficiency, openness, and people. An interesting part of one of the strategies reviewed is the Newcastle strategy in Australia where the representation of the process the city followed to reach engagement amongst the stakeholders. From there, a collaborative baseline is needed in order to assess weaknesses, strengths, and potential challenges of the city. This especially regarding interoperability and infrastructure needed for smart initiatives. Leadership and allocation of responsibilities and resources are also a key component for processes to move forward and guide stakeholders in the same direction. From the literature shown, frameworks for smart and sustainable assessment provide indicators to assess the process of smartization and sustainable development respectively. Their potential usage and feasibility should be assessed and research is particularly recommended to continue on this topic.

Data interoperability – When it comes to AQ and its hyper local monitoring, the potentials of its data analytics are fully explored when contrasted with other types of data. For Aalborg city, mainly traffic data was found to be available. In section 6.2 an explanatory example on how AQ data can be analysed jointly with transportation and built environment is shown. For this reason, sensors of this deployment were allocated accordingly to official traffic monitoring. It is foreseen that future work involves the aggregation and holistic analysis on both parameters. Indeed, this could potentially help Aalborg's sustainable mobility strategy on its active mobility or urban freight specific objectives, as an example. Here, future datasets as in human exposure, active mobility exposure, or medical records can help scale up data analytics.

8. Conclusions

The aim of this research was the deployment of a LCAQSN as it is stated in the following research question:

How can a low cost Air Quality Monitoring Sensor Network be implemented in the city of Aalborg?

The author considers that a LCAQSN was deployed successfully in the city of Aalborg and important experiences can be taken from its outcome. The methodology used for the sensor locations, programming, and data value chain has been described in section 6.

This pilot deployment allocated the best of the available data to perform a realistic analysis of the agglomerated critical areas to be assessed under an AQ point of view. Traffic and AQ monitoring data for Aalborg were identified and locations were strategically selected aiming for a more extended and interoperable analysis including data correlation. The potentials and opportunities of this LCAQMSN are presented as examples through the usage of metrics and data strategies for smart sustainable development. Multidimensional data aggregation and geo-visualization are concluded to be key strategies in order to reach full potential. Only when data interoperability is reached, the outcomes are projected to support decision making in planning, policy and design, considering a more extended and holistic analysis of the city system. However, literature and experience advise that data quality of low cost sensors have to be carefully examined on a previous stage.

As a pilot project, this research aimed to be the baseline and have first experiences to take into consideration for multiple further works. The sensors hardware makes them perfectly suitable for reallocation and changes to fit specific needs i.e. gas probes can be taken out or allocated when necessary. The coding programme that was used for this pilot can be rewritten and uploaded to the hardware if changes are needed according to the architecture proposed. The structure support made specifically for this pilot project can also be adapted to other scenarios when required since all the pieces and additions to the sensors are securely adjusted to the aluminium plaque.

In summary, the sensors can be reallocated, reprogrammed and adjusted according to new experiences or needed parameters for further research. Considerations from the discussion part of this report are encouraged to be taken into account. With time, innovation and further arrangements of this network are foreseen along with the deployment of additional data sources that could increase the potentials of this network data value chain. With this pilot deployment, the starting point of a LCAQMSN in the city of Aalborg is established.

Furthermore, a parallel project involving the usage of one set of AQ sensors attached to a professional drone is being developed. Its findings, jointly with the visualization of the first data outcomes from this LCAQSN are to be presented at the dissertation of the present Master Thesis. This part has not been included in this report due to the report's earlier submission deadline and the sensors installation time conflict.

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Annexes

```
/*
    Copyright (C) 2016 Libelium Comunicaciones Distribuidas S.L.
    http://www.libelium.com

    This program is free software: you can redistribute it and/or modify
    it under the terms of the GNU General Public License as published by
    the Free Software Foundation, either version 3 of the License, or
    (at your option) any later version.

    This program is distributed in the hope that it will be useful,
    but WITHOUT ANY WARRANTY; without even the implied warranty of
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    GNU General Public License for more details.

    You should have received a copy of the GNU General Public License
    along with this program.  If not, see <http://www.gnu.org/licenses/>.

    Version:           3.0
    Design:            David Gascón
    Implementation:    Yuri Carmona
*/

#include <WaspOPC_N2.h>
#include <WaspSensorGas_Pro.h>
#include <Wasp4G.h>
#include <WaspFrame.h>

// 4G PARAMETERS//
// APN settings
char apn[] = "internet";
char login[] = "";
char password[] = "";

// E-mail sender parameters
char sender_address[] = "XXXXXXX";
char sender_user[] = "XXXXXXX";
char sender_password[] = "XXXXXXX";

// E-mail SMTP parameters
char smtp_server[] = "smtp.aau.dk";
uint8_t smtp_security = Wasp4G::EMAIL_SSL;
uint16_t smtp_port = 587;
uint32_t counter = 0;

// E-mail to send
char receiver_address[] = "airq4aal@gmail.com";
char subject[] = "AQ from Node1"; // maximum: 100 bytes

//// define variable
uint8_t sd_answer;
uint8_t error ;

// sensors definition
Gas SO2(SOCKET_A);
Gas NO2(SOCKET_B);
Gas CO(SOCKET_C);
Gas CO2(SOCKET_F);

float temperature;  // Stores the temperature in °C
float humidity;   // Stores the realitve humidity in %RH
```

```
float pressure;   // Stores the pressure in Pa
float concSO2;  // Stores the concentration level in ppm
float concNO2;  // Stores the concentration level in ppm
float concCO;  // Stores the concentration level in ppm
float concCO2;  // Stores the concentration level in ppm

char info_string[61];
int status;
int measure;
char node_ID[] = "Gasses_Node1";

void setup()
{
  // open USB port
  USB.ON();
  USB.println(F("Gasses_Node1_HEX_VIA_EMAIL"));
  // Set the Waspmote ID
  frame.setID(node_ID);

    status = OPC_N2.ON();
    if (status == 1)
    {
        status = OPC_N2.getInfoString(info_string);
        if (status == 1)
        {
            USB.println(F("Information string extracted:"));
            USB.println(info_string);
        }
        else
        {
            USB.println(F("Error reading the particle sensor"));
        }

        OPC_N2.OFF();
    }
    else
    {
        USB.println(F("Error starting the particle sensor"));
    }

  //////////////////////////////////////////////////
  // Set 4G operator parameters
  _4G.set_APN(apn, login, password);

  //////////////////////////////////////////////////
  // Show APN settings via USB port
  _4G.show_APN();

  //////////////////////////////////////////////////
  // 1. Switch on the 4G module
  error = _4G.ON();
  if (error == 0)
  {
    USB.println(F("1. 4G module ready..."));

    ////////////////////////////////////////////////
    // 1.1. Reset e-mail parameters
    error = _4G.emailReset();

    if (error == 0)
```

```
    {
      USB.println(F("1.1. Reset e-mail parameters OK"));
    }
    else
    {
      USB.print(F("1.1. Error reset configuration. Code: "));
      USB.println(error, DEC);
    }

    ////////////////////////////////////////////////
    // 1.2. Set SMTP server
    error = _4G.emailSetServerSMTP(smtp_server);
    if (error == 0)
    {
      USB.println(F("1.2. SMTP server set OK"));
    }
    else
    {
      USB.print(F("1.2. Error set server. Code: "));
      USB.println(error, DEC);
    }

    ////////////////////////////////////////////////
    // 1.3. Configure SMTP server security and port
    error = _4G.emailConfigureSMTP(smtp_security, smtp_port);
    if (error == 0)
    {
      USB.println(F("1.3. Configure SMTP server OK"));
    }
    else
    {
      USB.print(F("1.3. Error configuring SMTP server. Code: "));
      USB.println(error, DEC);
    }

    ////////////////////////////////////////////////
    // 1.4. Set sender address
    error = _4G.emailSetSender(sender_address, sender_user,
sender_password);
    if (error == 0)
    {
      USB.println(F("1.4. Sender addres set OK"));
    }
    else
    {
      USB.print(F("1.4. Error set address. Code: "));
      USB.println(error, DEC);
    }

    ////////////////////////////////////////////////
    // 1.5. Save e-mail configuration settings
    error = _4G.emailSave();

    if (error == 0)
    {
      USB.println(F("1.5. Save configuration OK"));
    }
    else
    {
      USB.print(F("1.5. Error saving configuration. Code: "));
```

```
      USB.println(error, DEC);
    }
  }
  else
  {
    USB.print(F("1. Error starting module. Code: "));
    USB.println(error, DEC);
  }

  USB.println(F("*** Setup 4G done ***\n\n"));

  // Get free memory before the process
  USB.print(F("Free memory before (bytes/8K) :"));
  USB.println(freeMemory());

  //Set time on
  RTC.ON();
}

void loop()
{
USB.print(F("Time to wake up :")); USB.println(RTC.getTime());
USB.println(F("Time to measure"));
Utils.blinkLEDs(2000); //check point
    // 1a. Turn ON the gas sensors
    SO2.ON();
    USB.println(F("SO2 ON"));
    NO2.ON();
    USB.println(F("NO2 ON"));
    CO.ON();
    USB.println(F("CO ON"));
    CO2.ON();
    USB.println(F("CO2 ON"));

    // The sensor needs time to warm up and get a response from gas
    // To reduce the battery consumption, use deepSleep instead delay
    // After 3 minutes, Waspmote wakes up thanks to the RTC Alarm
    PWR.deepSleep("00:00:03:00", RTC_OFFSET, RTC_ALM1_MODE1, ALL_ON);
    Utils.blinkLEDs(2000); //check point
    USB.println(F("Wake up"));

    ///////////////////////////////////////////
    // 1b. Turn on the PM sensor, power on the OPC_N2 sensor.
    // If the gases PRO board is off, turn it on automatically.
    status = OPC_N2.ON();
    USB.println(F("PM ON"));
    if (status == 1)
    {
        USB.println(F("Particle sensor started"));
    }
    else
    {
        USB.println(F("Error starting the particle sensor"));
    }

  ///////////////////////////////////////////
  // 2. Read sensors
  Utils.blinkLEDs(2000);
  // Power the fan and the laser and perform a measure of 5 seconds
  measure = OPC_N2.getPM(5000);
```

```
  // Read the GAS sensor and compensate with the temperature internally
  concSO2 = SO2.getConc();
  concNO2 = NO2.getConc();
  concCO = CO.getConc();
  concCO2 = CO2.getConc();
  // Read enviromental variables
  temperature = CO2.getTemp();
  humidity = CO2.getHumidity();
  pressure = CO2.getPressure();
  // And print the values via USB
  USB.println(F("***************************************"));
  USB.println(F("Measurement performed"));
  USB.print(F("Temperature: "));
  USB.print(temperature);
  USB.println(F(" Celsius degrees"));
  USB.print(F("RH: "));
  USB.print(humidity);
  USB.println(F(" %"));
  USB.print(F("Pressure: "));
  USB.print(pressure);
  USB.println(F(" Pa"));
  USB.print(F("PM 1: "));
  USB.print(OPC_N2._PM1);
  USB.println(F(" ug/m3"));
  USB.print(F("PM 2.5: "));
  USB.print(OPC_N2._PM2_5);
  USB.println(F(" ug/m3"));
  USB.print(F("PM 10: "));
  USB.print(OPC_N2._PM10);
  USB.println(F(" ug/m3"));
  USB.print(F("SO2 concentration: "));
  USB.print(concSO2);
  USB.println(F(" ppm"));
  USB.print(F("NO2 concentration: "));
  USB.print(concNO2);
  USB.println(F(" ppm"));
  USB.print(F("CO concentration: "));
  USB.print(concCO);
  USB.println(F(" ppm"));
  USB.print(F("CO2 concentration: "));
  USB.print(concCO2);
  USB.println(F(" ppm"));
  USB.print(PWR.getBatteryLevel(),DEC);
  USB.println(F(" % "));
  USB.println(F("***************************************"));

  ///////////////////////////////////////////
  // 3. Turn off the sensors
  // Power off the NO2 sensor. If there aren't more gas sensors powered,
  // turn off the board automatically
  // (CO, NO2, and SO2 sensors are recommended to not be turned off due
to their lower power consumption)
  OPC_N2.OFF();
  CO2.OFF();

  ///////////////////////////////////////////////////
  // 4. Create Data frame using the Waspmote Frame class
  // Create new frame (ASCII)
   RTC.getTime();
```

```
  // Create new frame (ASCII)
  frame.createFrame(ASCII);
  // Set frame fields (Date from RTC)
  frame.addSensor(SENSOR_DATE, RTC.year, RTC.month, RTC.date);
  // Set frame fields (Time from RTC)
  frame.addSensor(SENSOR_TIME, RTC.hour, RTC.minute, RTC.second);
  // Add temperature
  frame.addSensor(SENSOR_GASES_PRO_TC, temperature);
  // Add humidity
  frame.addSensor(SENSOR_GASES_PRO_HUM, humidity);
  // Add pressure
  frame.addSensor(SENSOR_GASES_PRO_PRES, pressure);
  // Add PM 1
  frame.addSensor(SENSOR_GASES_PRO_PM1, OPC_N2._PM1);
  // Add PM 2.5
  frame.addSensor(SENSOR_GASES_PRO_PM2_5, OPC_N2._PM2_5);
  // Add PM 10
  frame.addSensor(SENSOR_GASES_PRO_PM10, OPC_N2._PM10);
  // Add SO2 concentrations
  frame.addSensor(SENSOR_GASES_PRO_SO2, concSO2);
  // Add NO2 concentrations
  frame.addSensor(SENSOR_GASES_PRO_NO2, concNO2);
  // Add CO concentrations
  frame.addSensor(SENSOR_GASES_PRO_CO, concCO);
  // Add CO2 concentrations
  frame.addSensor(SENSOR_GASES_PRO_CO2, concCO2);
  // Add battery level
  frame.addSensor(SENSOR_BAT, (uint8_t) PWR.getBatteryLevel());
  //show actual Frame
  frame.showFrame();

  ////////////////////////////////////////////////
  // 5. Switch ON
  error = _4G.ON();
  if (error == 0)
    {
    USB.println(F("1. 4G module ready..."));

    ////////////////////////////////////////////////
    // 6. Send e-mail
    Utils.blinkLEDs(2000);
    error = _4G.emailSend(receiver_address, subject, (char*)
frame.buffer) ;
    if (error == 0)
    {
      USB.println(F("2. Sending e-mail OK"));
    }
    else
    {
      USB.print(F("2. Error sending e-mail. Code: "));
      USB.println(error, DEC);
    }
    }
  else
    {
    // Problem with the communication with the 4G module
    USB.print(F("1. 4G module not started. Error code: "));
    USB.println(error, DEC);
    }
```

```
  /////////////////////////////////////////////////
  // 7. Powers off the 4G module
  USB.println(F("3. Switch OFF 4G module"));
  _4G.OFF();

  USB.println();
  USB.println();

  // Get free memory after the process
  USB.print(F("Free memory after (bytes/8K) :"));
  USB.println(freeMemory());

  ////////////////////////////////////////////
  // 8. Sleep
  // Go to deepsleep until time to measure (on minute 00, 15, 30 and 45)
USB.print(F("Time :")); USB.println(RTC.getTime());
if ((RTC.minute > 0) && (RTC.minute <= 12))
  {
  USB.print(F("Time to sleep until minute 12"));
  USB.println();
  PWR.deepSleep("00:00:12:00", RTC_ABSOLUTE, RTC_ALM1_MODE4, ALL_OFF);
  }
else
{
    if ((RTC.minute >= 13) && (RTC.minute <= 27))
    {
    USB.print(F("Time to sleep until minute 27"));
    USB.println();
    PWR.deepSleep("00:00:27:00", RTC_ABSOLUTE, RTC_ALM1_MODE4, ALL_OFF);
    }
    else
    {
      if ((RTC.minute >= 28) && (RTC.minute <= 42))
      {
      USB.print(F("Time to sleep until minute 42"));
      USB.println();
      PWR.deepSleep("00:00:42:00", RTC_ABSOLUTE, RTC_ALM1_MODE4,
ALL_OFF);
      }
      else
      {
        if ((RTC.minute >= 43) && (RTC.minute <= 57))
        {
        USB.print(F("Time to sleep until minute 57"));
        USB.println();
        PWR.deepSleep("00:00:57:00", RTC_ABSOLUTE, RTC_ALM1_MODE4,
ALL_OFF);
        }
        else
        {
        USB.print(F("Time to sleep until minute 12"));
        USB.println();
        PWR.deepSleep("00:00:12:00", RTC_ABSOLUTE, RTC_ALM1_MODE4,
ALL_OFF);
      }
    }
}
}
}
```