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Low-cost air quality sensors: an opportunity to raise awareness and improve air pollution monitoring

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List of Acronyms

AWAC	Agence Wallonne de l'Air et du Climat
CPES	Cellule Permanente Environnement-Santé
DIY	Do It Yourself
DQO	Data Quality Objectives
IBGE	Institut Bruxellois pour la Gestion de l'Environnement
ISSeP	Institut Scientifique de Service Public
IRCELINE	Intergewestelijke Cel voor het Leefmilieu (IRCEL) - Cellule Interrégionale de l'Environnement (CELINE)
LoRaWAN	Low Range Wide Area Network
NDIPHE	National Dutch Institute for Public Health and the Environment
PARES	Programme d'Actions Régionales Environnement-Santé
PM	Particulate Matter
REU	Relative Expended Uncertainty
TEOM-FDMS	Tapered Element Oscillating Microbalance - Filter Dynamic Measurement System
VMM	Vlaamse Milieumaatschappij
VUB	Vlaamse Universiteit Brussels
WHO	World Health Organization

Introduction

In May 2018, the World Health Organization (WHO) published a report explaining that Particulate Matter, an air pollutant composed of droplets and solid particles, caused 4.2 million premature deaths worldwide in 2016. Indeed, exposition to Particulate Matter increases the risks of cancers, cardiovascular and respiratory diseases. Human Particulate Matter emissions, which count for more than twice the amount of natural emissions, are mostly produced by the sectors of transport, energy, and agriculture (United States Environmental Protection Agency, 2015).

During the month of July 2018, Europe and Northern America have suffered from an important heat wave. Heat fosters the chemical reactions producing Particulate Matter (Foobot, 2018), therefore, this heat wave has caused a higher level of Particulate Matter concentration in the atmosphere.

The aim of this thesis is to understand if and how low-cost air quality sensors measuring Particulate Matter deserve to be used by Belgian public institutions responsible of air quality monitoring. Low-cost sensors create the opportunity to have more measurement sites and to raise awareness among citizens. Monitoring ambient air pollution is necessary to know when, how, and to what extent actions should be taken to reduce it. Raising awareness is necessary for people to realize the level of pollution they are exposed to, as well as its impact on their health. Becoming conscious of this could be an incentive for them to adapt their lifestyle to a less polluting one. Such adaptation could be avoiding to use the car or abstaining from wood burning.

This thesis only focuses on the low-cost sensors' accuracy and the public's awareness. People's behavior modification is not developed, neither are public institution's decisions to reduce air pollution.

This thesis is divided in three chapters:

- The first section of the first chapter has the purpose to expose a non-profit organization, Influencair, which aims at deploying low-cost air quality sensors. There, the goals and origin of the project are explained in details. The second section focuses on the low-cost sensor. The technology involved is detailed, explaining how the sensors are built and how they measure Particulate Matter concentrations. Then, an overview of their accuracy is stated. The measurements are not analyzed in detail but are rapidly compared to the official monitoring stations ones, which gives us a glimpse of the low-cost sensors' accuracy. The third section of the first chapter describes the official monitoring stations' technology and the models based on their measurements. Those models provide a high resolution air quality map of Belgium, and are used, among others, to communicate the current air quality to the broad public.

- The second chapter focuses on the Belgian public institutions working on air quality monitoring. Their scope, responsibilities and visions are disclosed. As air quality is a regional competence, this chapter has been divided in four sections: one for each region and one focusing on an inter-regional organization (the Belgian Interregional Environment Agency). The aim of this chapter is to understand if and how each of them could be interested in the low-cost sensors.

- The last chapter is mostly based on things that have been learned in chapters one and two. First, it extensively explains the methodology to be followed to test the low-cost sensor's accuracy. The recommendations in this section have been based on tests that have already been done for other low-cost sensors (Castell et al., 2017; Spinelle et al., 2015), and on a European document (European Commission, 2010) explaining the established methodology. This section explains how co-locating the sensors with monitoring stations during 6 months and comparing their measurements can assess the sensor's accuracy. The second section suggests possible scenarios depending on the accuracy test's results. Each of them explains what public institutions can do with the sensors depending on their veracity. The section then discusses the opportunity to exploit the sensors for each public institution, depending on their vision and responsibilities.

Concerning the accuracy assessment, the actual testing has yet to be done, as this thesis only provides the methodology. Additional interviews could be conducted in order to know about each public institution's view on low-cost sensors.

Chapter 1

Low-cost sensors and monitoring stations

1.1 Influencair

The purpose of this section is to outline the project, Influencair. It will explain what it does, what it tries to achieve, and its barriers.

Figure 1.1: Logo of the project. Made by Xavier Ralet and m Point Production Brussels.

Influencair is a group of citizens who want to measure and map local air pollution levels in Brussels. To do so, they aim to build a comprehensive network of 150 Particulate Matter sensors covering the whole city area by the end of 2018. To achieve this goal, they gather every other Tuesday. They work on the sensors' hardware, analyze the collected data, plan workshops and try to find partners to reach more citizens.

This section will expound Particulate Matter and its effects on health before describing the project in more details.

1.1.1 Particulate Matter

The sensors measure Particulate Matter, which is a pollutant composed of droplets and solid particles, they are measured in µg/m^3. Their size vary, as some of them can be seen by the human eye while others require powerful microscopes. We distinguish Particulate Matter which has a diameter less than or equal to 10 µMeters and 2.5 µMeters, respectively called PM_{10} and $PM_{2.5}$, or coarse and fine particles (United States Environmental Protection Agency, 2015). There are also ultrafine particles, called $PM_{0.1}$, which have a diameter smaller than 0.1µMeter, but this paper does not discuss it as it is rarely monitored and it is not regulated by European law.

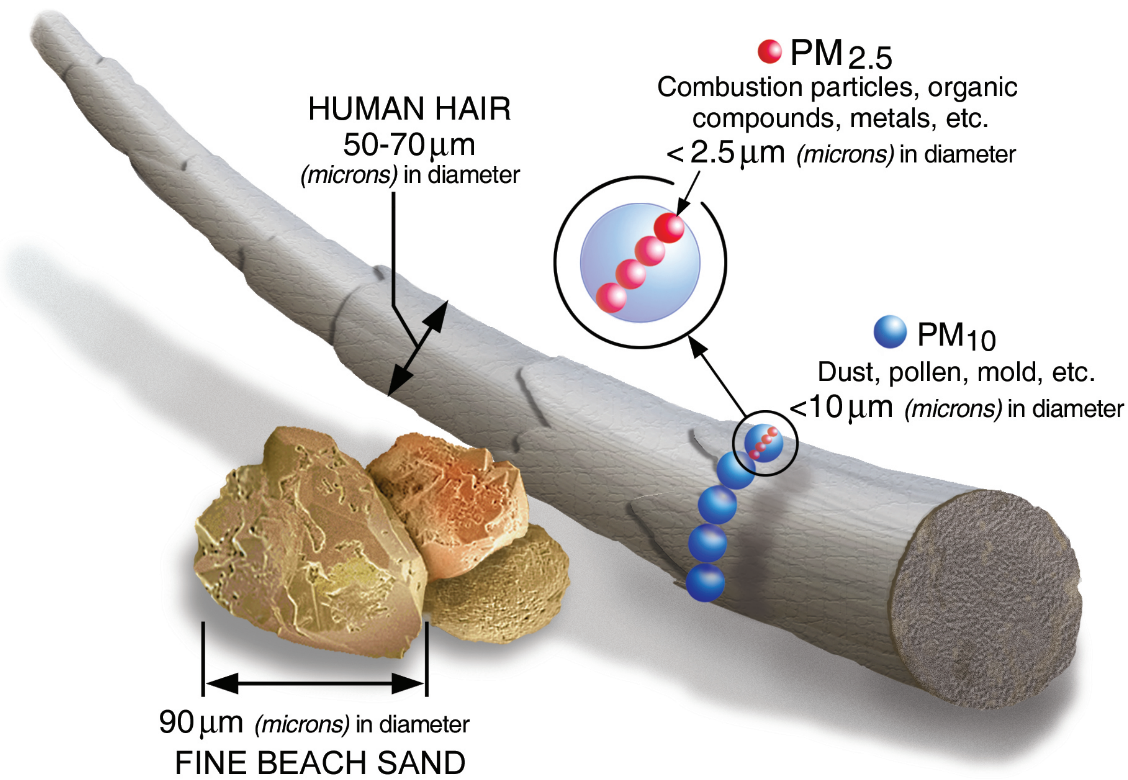

Figure 1.2: Size of PM_{10} and $PM_{2.5}$ compared to human hair and fine beach sand. Source: United States Environmental Protection Agency, 2017

Those two kinds of pollutants have different behaviours in the atmosphere. $PM_{2.5}$ can travel long distances in the air while PM_{10}'s dispersion distance is more limited (United States Environmental Protection Agency, 2015). We distinguish primary particles from secondary particles. The former are particles that are directly emitted in the atmosphere, they are not bigger than 2.5 µMeter. They include dust from roads and particles coming from combustion (United Stated Environmental Protection Agency, 2016). Secondary particles are generated by chemical and mechanical reactions in the atmosphere. Those are bigger than 2.5µMeter and their origin is hard to tell as they come from clusters of primary particles (Amaral et al., 2015).

We are mostly interested in particles smaller than 10 µMeter because bigger ones are filtered by the nose and the upper airway of the respiratory system. Smaller ones have the ability to get deep into the lungs and in the circulatory system, and thus to affect human health (United States Environmental Protection Agency, 2016). According to the European Environment Agency, 2014, and the World Health Organizationy, 2018, Particulate Matter is responsible of:

- Causing or aggravating cardiovascular and lung diseases, heart attacks and arrhythmias
- Causing cancer
- Leading to atherosclerosis, adverse birth outcomes and childhood respiratory diseases
- Causing premature deaths of 500 000 people in the European Union

The World Health Organizationy, 2018, recommends the average level of $PM_{2.5}$ and PM_{10} to which people expose themselves not to be over respectively 10µg/m^3 and 20µg/m^3. Meanwhile, the legal limits not to exceed are defined by the Air Quality Directive 2008/50/EC. Concerning PM_{10}, the yearly average should not exceed 40µg/m^3, and the daily average should not exceed 50µg/m^3 more than 35 times per year (Annex XI of the directive). As for $PM_{2.5}$ concentrations should not exceed 20µg/m^3 on a three-year average. This objective should be achieved by 2020 (Annex XIV of the directive). The directive also defines reduction targets depending on the averaged concentration of $PM_{2.5}$ in each European country (see table 1.1).

Initial concentration in µg/m^3	Reduction target in percent
≤ 8.5	0%
]8.5 ; 13[	10%
[13 ; 18[	15%
[18 ; 22[	20%
≥ 22	All appropriate measures to achieve 18 µg/m^3

Table 1.1: National reductions - Reduction targets of national yearly averaged exposition to $PM_{2.5}$ to achieve by 2020 depending on the average exposure.

On 17^{th} May 2018, the French newspaper "Le Monde" explained in one of its articles that France has been sued by Belgium for exceeding the values concerning NO_2 defined by the Directive. The article also explains that some European countries tend to go beyond the limit values when it comes to PM_{10}. The Court of Justice of the European Union has condemned two countries so far, Poland and Bulgaria, which have very high level of air pollution. This is mostly due to wood heating practiced by households.

1.1.2 Origin

The project Influencair was initiated by Civic Lab Brussels, which started in March 2017. Civic labs are regular gatherings of citizens who work on projects that aim at improving local communities' life. In Belgium, Civic Labs can be found in Brussels, Leuven and Gent. Civic Lab Brussels was an initiative of Open Knowledge Belgium which is a non profit umbrella organisation for Open Knowledge and Open Data initiatives. According to Dietrich et al., 2009, Open Data is data that can be freely used, re-used and redistributed by anyone - subject only, at most, to the requirement to attribute and sharealike. Open Knowledge Belgium promotes availability of the data so that knowledge creates power for the many, not the few.

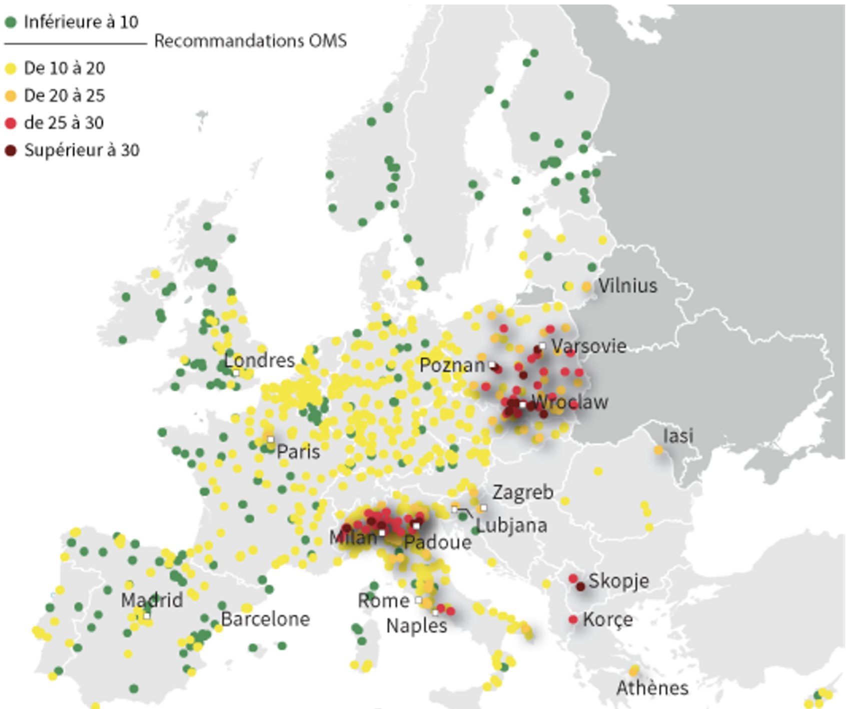

Figure 1.3: Yearly averaged concentrations of $PM_{2.5}$ in $\mu g/m^3$, 2015. Source: Qualité de l'air en Europe, Agence Européenne de l'Environnement, 2017.

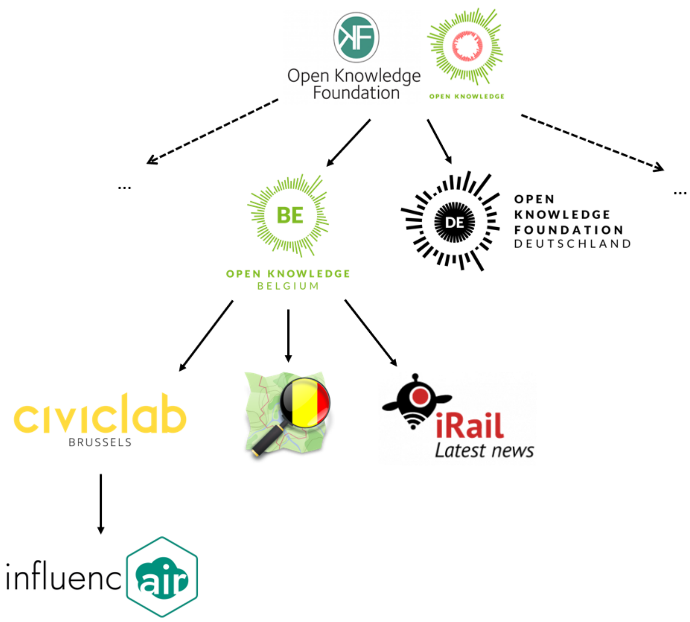

Figure 1.4: Diagram of Open Knowledge initiatives

1.1.3 Goals

Here is the list of the objectives pursued by Influencair, followed by a brief explanation of each of them.

- Raise more awareness about air quality and its health effects
- Set an example of real-time open data which anyone can freely access, use, modify, and share for any purpose
- Increase the amount of local measurements, which are complementary to the data from official government stations
- Bridge the gap between science and a wider audience

Awareness is critical to improve the capacity of people to address environmental issues. Only then, the passive awareness can be translated into active concerns and behaviours (Teksoz, 2011). Those behaviours can be linked to the way people travel, heat their home, etc. Although Influencair wants to raise awareness, it is important for them not to directly force people to change their behavior. The project wants to raise awareness, considering it is then up to the citizens to change or not their habits. They believe it is not their role to tell people what they should do. The Vrije Universiteit Brussel (VUB) is currently setting up a research to understand the sensors' effects on people's awareness about air pollution. The results should be out by September 2018. An official research is the best way possible to assess the impact or not on awareness. However, there is already been observed that people who build and set up a sensor at home tend to care more about the air they breathe, says Toon Nelissen, entrepreneur and founder of Influencair.

The idea of open data is that private and public organizations as well as individuals can make the data they generate available so it can be used, re-used and redistributed by anyone. Opening data has a huge economic potential as it fosters innovation, new products and services development, more efficient operations, higher productivity, reduction of risks, and much more (Manyika et al., 2013; van Schalkwyk and Verhulst, 2017). In this particulat case, building an open data set has a few perks.

1. First and foremost, it empowers any citizen who can work on the data set and try to understand air pollution's behaviour. It is currently being done in Leuven

by Maarten Reyniers, researcher at the Royal Meteorological Institute of Belgium, and Kris Vanherle, researcher at Transport & Mobility Leuven. They publish a lot of interesting air quality visualization analysis on Facebook and Twitter. There is also a Slack[1] group of data analysis enthusiasts working together to understand and interpret the data. Their objective is to find ways to check the quality of the data provided, find solutions on how to improve it, and understand pollution's behaviours and trends. On the 28th April and on the 3rd March, workshops were organized so that citizens could learn how to extract the data and use a specific Python library created specifically for analyzing this particular data set. All the information about the workshop is available on Github here.

2. Secondly, it allows direct improvement of the software and hardware. The fact that all the information is open makes it possible for people to work freely on it and re-use it for commercial and non commercial purposes. The information being "fluid" allows people to improve the hardware, the software, and to find new purposes for those. In Leuven, citizens found ways to make sensors more compact without reducing the quality of the measurements. A citizen in Gent developed a fast and easy way to flash the software into the sensor. In Brussels, another citizen developed and built a Printed Circuit Board (PCB) that is cheap to produce and leads to a much easier assembling of the sensor. All this would not have been possible if all the information had not been open.

3. Thirdly, thanks to this openness, this kind of initiative can be undertaken by anyone anywhere on earth, as long as they have access to internet. The initiative of citizen measuring air quality has been launched in Stuttgart, by OK Lab Stuttgart, which is part of the Code for Germany program of the Open Knowledge Foundation Germany. Their goal is to promote transparency development, open data and citizen science. Citizen science is a research technique which includes the public in the data gathering process (Bonney et al., 2009). When they developed the sensor, they made the software open source, and they explained how to order the components and how to assemble them. The fact that they made it open led to many citizen-driven organizations to replicate their work, expanding the number of measurements obtained around the world, and particularly in Europe.

[1] Slack is a free team communication software.

Brussels contains many citizen-driven organizations and movements linked to air quality. Some of them claim that the government is trying to hide data, and does not show the actual air pollution. At Influencair, they do not agree with this view. On the contrary, they believe that the best way to achieve better air quality is through close collaboration with all concerned actors. There are currently 6 official air quality measurement stations set up by the government inside the wide belt of Brussels.

While the compliance with the limits set by the Directive is achieved through the data points provided by the monitoring stations, Belgium also works on air quality maps that are created through models (see figure 1.5, page 12). Unfortunately, the models used are very complex and not scientifically valid. That is the reason why it is explicitly written at the bottom of the web page displaying the map "These data are not validated: they should not be used for any study whatsoever.". Having more measurement points can help validate and improve those models. It is the goal of Curieuzeneuzen, a citizen-science project organized by Universiteit Antwerpen, during which 20,000 participants measure NO_2 in Flanders during the month of May to improve the model they use to map NO_2 concentration in Belgium.

Bridging the gap between science and a wider audience means, in this context, trying to generate interest among people for hardware, software, and data analysis. On the 28th April and on the 3rd March, Dominik Rubo has set up workshops to teach people how to extract data provided by the sensors. The goal was to teach participants how to use the Jupyter notebook, a web-based interactive computational environment, by applying it to the data provided by the sensors. There are other contexts in which this can be done. For example, organizing such workshop in schools can bring interest to students about data analytic and coding. In addition, building the sensors with a class is an excellent opportunity to develop interest among students for technology. VRT Sandbox already does such thing in primary school classes with the SteamBox. This project aims at building an interactive stair with children. All the information and the required material are provided in the SteamBox. Perhaps it is possible in the future to do such thing with the air quality sensor. In addition, it is also a way to create interest of people for technology in general.

Air pollution is a complex phenomenon. When people get interested in sensors, they wonder what they measure exactly. There are indeed many different initiatives, measuring

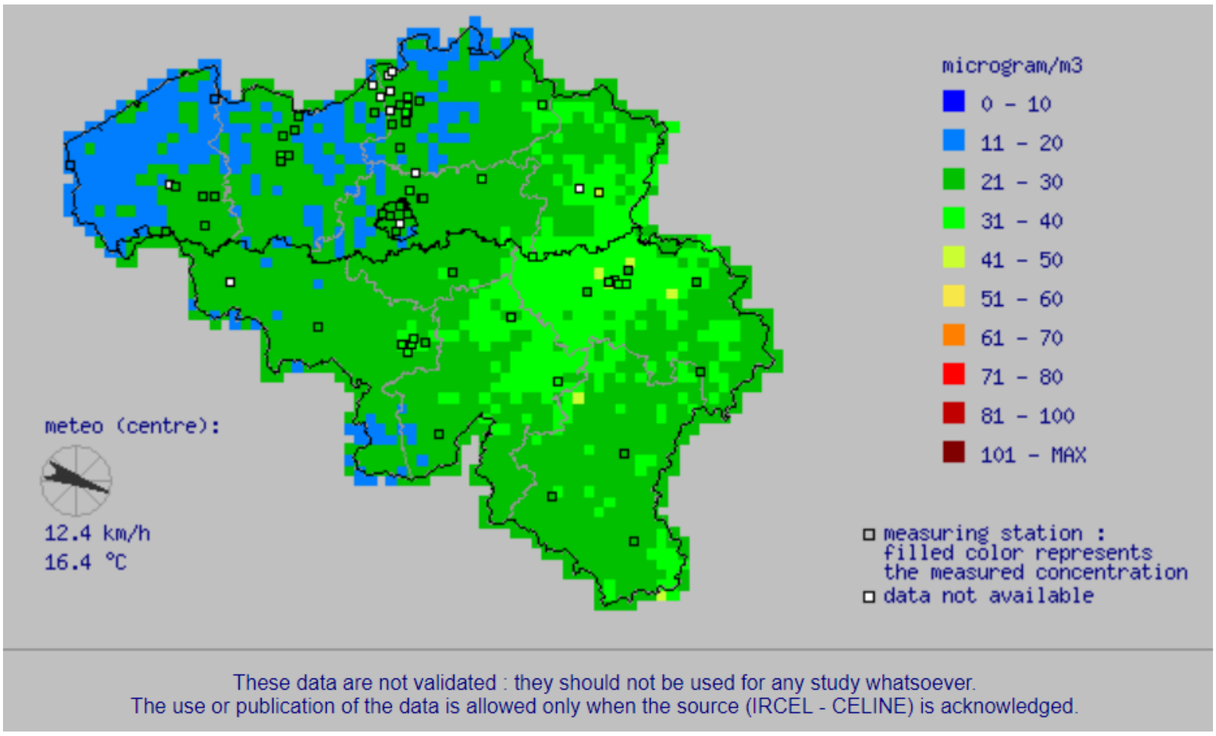

Figure 1.5: PM_{10} levels on Thursday 10/05/2018: situation at 12:00 - Made by the Belgian Interregional Environment Agency (IRCELINE)

different pollutants, which have all different impact on health. People's interest in air pollution is a good opportunity for them to learn how it works with a scientific approach.

1.1.4 Barriers

Influencair is a project with a lot of interesting goals, supported by very engaged people. However, like every project, a few obstacles hinder the achievement of their objectives. Being aware of these obstacles is an important step to know what to improve and where to put resources.

Influencair is a volunteer driven organisation. That means everyone involved has a job or another main activity that is of higher priority than this project. Considering that, people tend to avoid taking over responsibilities, hardly finding the time to unlock the required resources to deploy sensors or analyze the collected data. It is also sometimes hard for Influencair to get close to partners and maintain their relationship with them as this also requires time.

In addition, Influencair's collaborators only gather at Civic Labs Brussels which take place once every other Tuesday evening. Again, this means very few meetings and time to coordinate the activities and go further in the analysis. Also, this particular Civic Lab in Brussels aims at working on more than this air quality project. There are other open projects in the scope, reducing the already limited time available to work on air quality. Finally, Civic Labs are open and inclusive gathering, which means new people come at every meeting. It requires time to explain them the project and getting them on board, without any certitude that they will get involved in any way.

1.2 Low-cost sensors

This section aims at describing the different aspects of the low-cost sensors, answering the sub-research question "How do the low-cost sensors work and what are their strengths and weaknesses?".

1.2.1 Technology

The sensor is built by ordering all the necessary pieces then assembling them together. To get the lowest possible price, it is necessary to order some pieces on the internet and others in a DIY shop. Figure 1.6, page 15 shows an exhaustive list of the pieces required to build an air quality sensor.

First, a firmware needs to be implemented in a Core Processing Unit (CPU), so it can communicate the information collected by the sensor through the internet. The firmware has been developed by OK Lab Stuttgart and is open source. To flash the firmware in the CPU, people need to connect it to their computer, download the firmware, a driver, and the software Arduino. Then a command that is provided by OK Lab Stuttgart has to be put in the command prompt of the computer while the CPU is plugged in the computer, the computer needs then 3 to 5 minutes to flash the firmware. There are many tutorials on how to do it, anyone with basics computer knowledge can do it.

Once this is done, the CPU, the humidity sensor, and the Particulate Matter sensor can be connected together. Then, the 20cm flexible cable is attached to the PM sensor so it can vacuum air correctly, and all the pieces are tight together with cable ties to form a compact structure. The USB cable is then plugged into the CPU, and the sensor shown on figure 1.7, page 15, can be put in the elbow pipe. The latter's purpose is to protect the sensor from the humidity, the sun, and everything that could damage the sensor. When the sensor is put outside a window and plugged into an electrical outlet, it can be easily connected to the WiFi of the household/organisation, and it will start collecting data.

Low-cost sensors only measure Particulate Matter thanks to the SDS011, and humidity and temperature via the DHT22. In this section, we are only interested in the Particulate Matter sensor, as it is the critical part of the whole sensor. The SDS011 has been developed by Inovafit, a spin-off from the university of Jinan in China. It is an optical sensor (for more details on the different technologies, see section 1.3.1, page 26). It produces a laser beam, emitted by a LED, which is deviated by the particles in the vacuumed air. A photometer detector then measures the light that has been scattered (Amaral et al., 2015). The sensor then translates the beam's refraction to a quantity of Particulate Matter per cubic meter ($\mu g/m^3$). This information is converted to a concentration of PM. It is done by assuming the shape of the particles to be spherical. It also uses an algorithms to

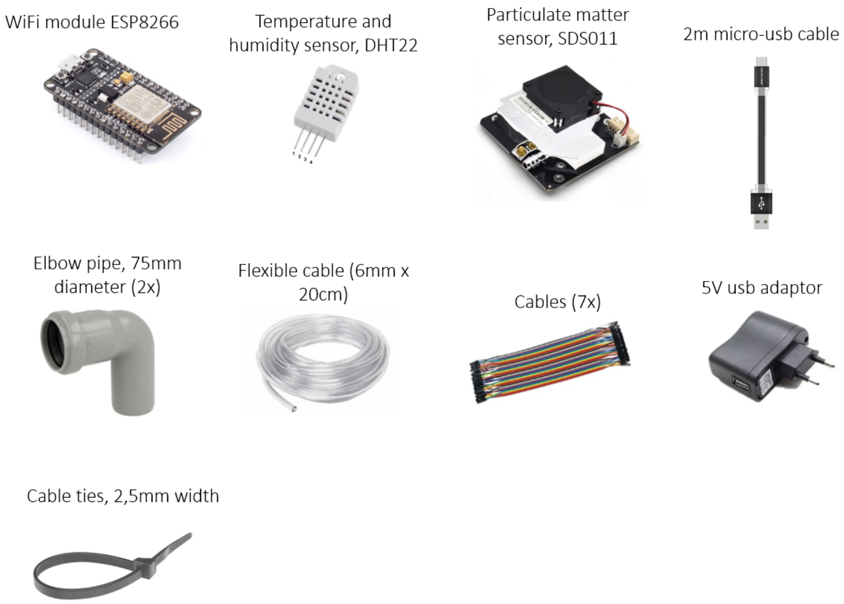

Figure 1.6: Required pieces to build a DIY air quality sensor.

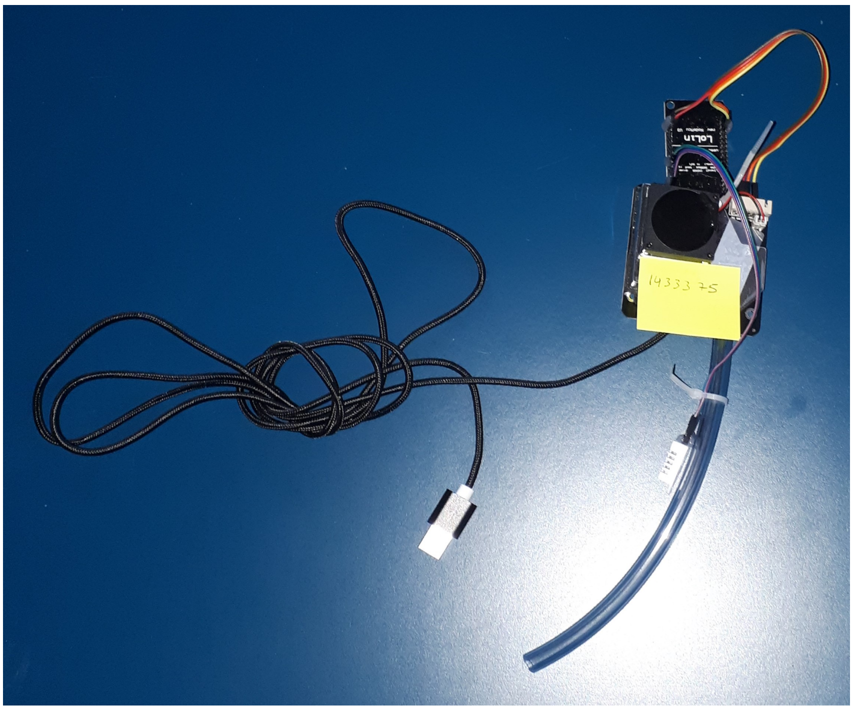

Figure 1.7: Assembled sensor ready to be put in the casing.

estimate the density distribution of the particles. There are patents for the SDS011, and its CPU cannot be reversed-engineered (World Air Quality Index, 2016), so it is currently impossible to know exactly how the size distribution algorithm works.

In addition, Influencair is currently developing LoRaWAN sensors. LoRaWAN, which is short for "Low Range Wide Area Network", is the protocol used to link devices to the internet without the need for them to be connected to a local router. It is practical to get measurements in areas that do not have any WiFi coverage. However, this kind of sensor is still in a prototype phase so it will not be discussed in detail in this paper. All the sensors deployed by Influencair are stationary, as mobile sensors cannot be used for mapping averages, it is very unpractical for serious analysis (O. Peeters, personal communication, March 3, 2018).

1.2.2 Measurements

This section aims at analyzing the quality of the measurements obtained by the sensors as described above. The objective is to assess if they are accurate enough to be used and spread.

Official monitoring stations are certified once they comply with the Data Quality Objectives. They have been tested and approved by national laboratories that are accredited by the EU/ISO 17025:2005, which defines the general requirements for testing and calibration (Directive 2008/50/EC). As those monitoring stations have been exhaustively tested, they are the best reference point to test the accuracy of the sensors.

Although the accuracy of the data has not been scientifically tested, three arguments can be put forward to support the idea that relatively good estimations of air quality have been observed.

1. First, there is a quite good matching between the low-cost sensors and the monitoring stations on a national level. The SDS011 is widely used and spread in Germany. The propagation has been mostly done by Luftdaten, an initiative of Code for Germany, which promotes citizen science and technology. Thanks to all the sensors deployed there and in the countries around Germany, they could draw a map of air quality in Europe, using data collected by low-cost sensors and monitoring stations.

Correspondence between the data collected by the SDS011 sensors and the monitoring stations used by the European Environment Agency can be found below on figure 1.8.

2. Secondly, the same correspondence has been observed at local level. Leuvenair, the equivalent of Influencair in Leuven, has set up on its website the possibility to compare the low-cost sensors' measurements in Leuven with the measurements of the Aarschot's monitoring station. Even though the station is located more than 7 Km away, we can see good correlation between the data provided by some SDS011 sensors and the one in Aarschot. Below, on figure 1.9, is an example of such correlation. The data shown by this fugire were collected by the sensor situated out of town, near Aarschot (north-east from Leuven), this is probably why the measurements are so similar.

3. Thirdly, the National Dutch Institute for Public Health and the Environment (NDIPHE) has conducted an experiment to test the accuracy of the data collected by the SDS011. They spread 110 lw-cost sensors in the end of 2017 in The Netherlands. After one month of measurements, they compared the data collected with the ones from the 40 official monitoring stations located in the Netherlands. Joost Wesseling (NDIPHE) presented this experiment at The Things Network Conference 2018 in Amsterdam. The NDIPHE is pretty satisfied with those results, considering that the calibration they have made was very small, said Joost Wesseling. The figure 1.10 below shows the corelation between the sensors and the monitoring stations. They estimate that the low-cost sensors can provide valuable complementary data to the ones from monitoring stations, and believe that a big amount of those sensors could replace some official monitoring stations in the future. In addition, Olav Peeters, from IRCELINE, said at the end of a presentation on the 3rd March that they are also open to find synergies between low-cost sensors and official monitoring stations, which is an encouraging statement.

However, it is important to raise the biggest downside of the low-cost sensors. The problem comes from the technology used and humidity. As the sensor works with a scattered laser beam, it can also be deviated by the water particles caused by rains. What happens then is that the sensor's measurements go abnormally up when it is raining. Citizens and researchers referred to in section 1.2 are already looking at ways to correct

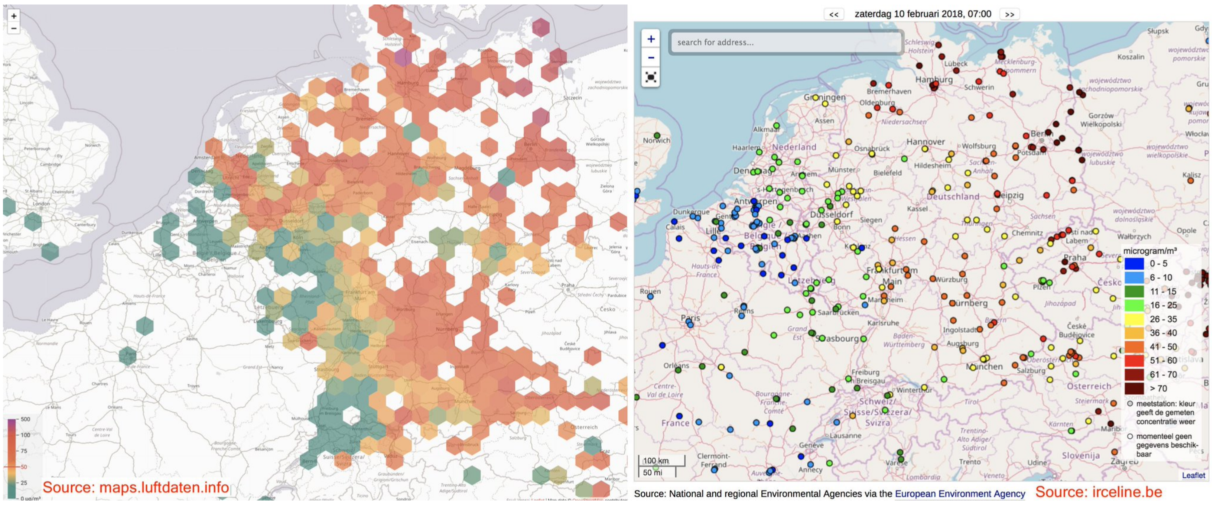

Figure 1.8: Comparison of the Luftdaten.info map using SDS011 sensors (left) and the European Environment Agency using air quality monitoring stations (right), 10th Ferbruary 2018. Sources: http://deutschland.maps.luftdaten.info/#6/51.165/10.455 and http://www.irceline.be/en/air-quality/measurements/particulate-matter/europe/pm25.

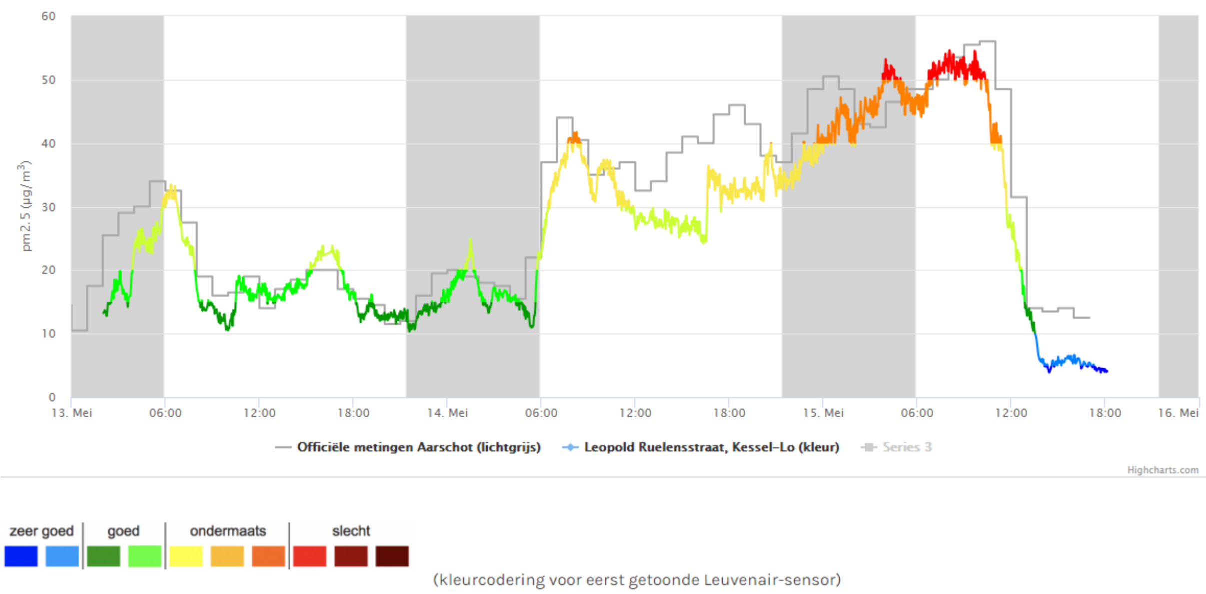

Figure 1.9: Comparison of the the $PM_{2.5}$ levels between the Aarschot monitoring station (Grey) and the low-cost sensor located Leopold Ruelensstraat in Leuven (colored), between 13th May and 16th May. Source: https://leuvenair.be/in-detail/grafieken/.

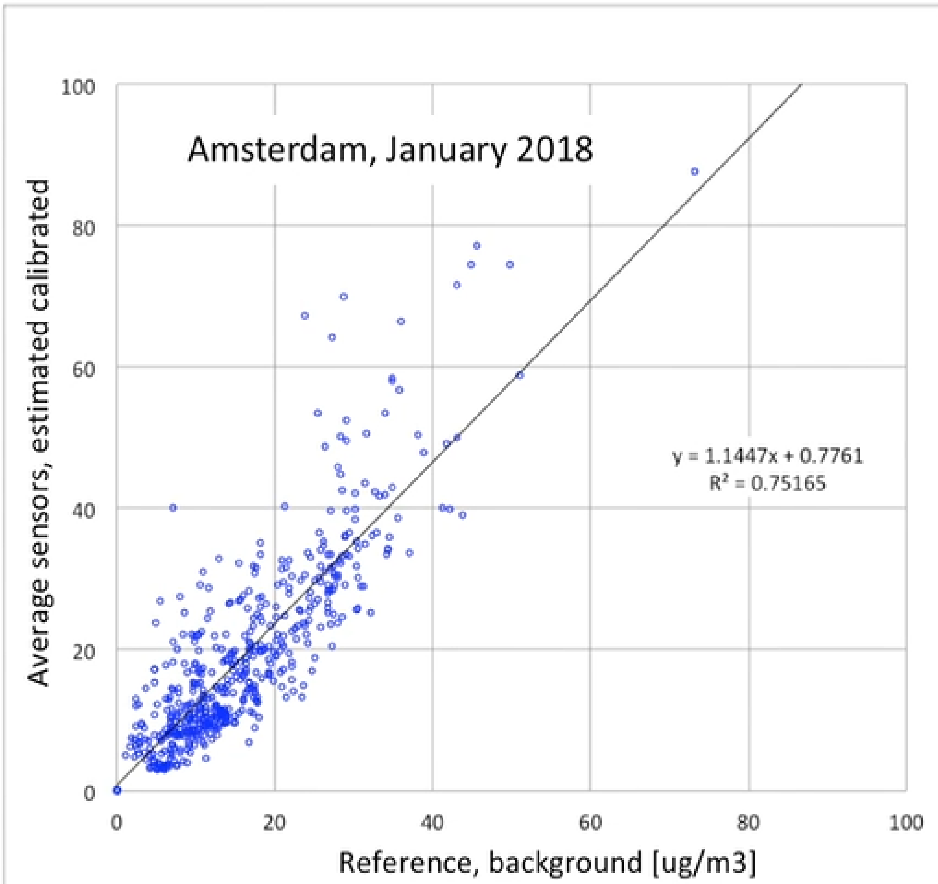

Figure 1.10: Comparison of the averaged calibrated measurements of PM_{10} of the SDS011 sensors (y axis) with the measurements of the monitoring stations of the Netherlands (x axis) in µg/m^3. Source: National Dutch Institute for Public Health and the Environment.

the data thanks to the humidity sensor DHT22 connected to the SDS011. But so far, the overall conclusion is that the data should not be used when there is a certain level of humidity, which can be problematic if the sensors were to be set up in very rainy areas. If no way of correcting the data is found, it is thus important to either drop it or to clearly mention this problem on the maps and when deploying sensors in people's houses.

When comparing the low-cost sensor's measurements with the ones from monitoring stations, it seems good enough to raise awareness and provide a rough estimation of air pollution in relatively dry areas. However, it is necessary to conduct a proper testing of the measurement's accuracy to know if they can really be used for scientific applications like epidemiology, or to improve the official models mapping air quality. In addition, it is urgent to find a way to calibrate the data during rainy days.

1.2.3 Building and deploying

In total, for one low-cost sensor, all the pieces come to an approximate total of €30, depending on the suppliers. To get the pieces for such a low price, it is necessary to order some on the internet and others in a DIY store.

There are different ways by which people can get a sensor.

1. The first approach is to order and build it by oneself at home. To do so, users need to find the information about where the necessary pieces can be bought, how to flash the firmware into the Core Processing Unit, and how to link the sensor to the main database. This approach can be quite time consuming as finding the information is not always easy. It can also require more or less effort to flash the firmware into the CPU, depending on people's competence in informatics. All the resources are dispersed on the internet and sometimes it requires a lot of research to find the right video tutorial or the right list of pieces. Nevertheless, a lot of people managed to do it by themselves. People following this approach are mostly individuals that are already interested and aware of the importance of air quality. Thus, this approach helps bringing new data on air quality, but will have a smaller impact into creating a community of people caring for the air pollution.

2. The second possible approach is to buy it from an organisation like Influencair or Leuvenair. The latter builds it and then asks for a financial compensation to cover

the costs of the pieces. People using such approach are either individuals or organizations. The organizations doing this usually want to raise awareness about air quality by showing actual measurements in the area where their employees/members are located. It was the case with BRAL in Brussels, which bought 15 sensors to Influencair to set them up in schools and other places. This is a way to reach communities without the need to understand how the sensors work. It has the advantage of reaching a lot of people at the same time. However, it is sometimes complicated for citizen-driven organizations like Influencair to set up the sensors, as it is done on a voluntary basis and it requires quite a lot of time to order, build and set up the sensors. Another problem with this approach is that individuals and organizations who get a sensor that way are less knowledgeable about it. They thus tend not to look for solutions when technical problems arise for example.

3. The third approach is to go to workshops organized by citizen-driven organizations in order to build one. Participants pay for the pieces that have been ordered for them and get to understand how the sensor works, how it should be set up, and other useful information about the data and air pollution. This is the approach Influencair and Leuvenair try to promote by inviting people to come and build their own sensor at their Civic Labs, every other week, or at special workshops. The advantage of this approach is that citizens get to learn how to take care of their sensors and how to interpret the data. Then, they can also learn how to access the database if they want to do further analysis of the data. This approach raises less awareness than the second one, but has a bigger emphasis on citizen science.

1.3 The Belgian monitoring stations

This section aims at describing the different aspects of the monitoring stations used in Belgium, answering the sub-research question "How do the monitoring stations work and what are their strengths and weaknesses?".

1.3.1 Technology

In Belgium, official monitoring stations can measure 8 types of pollutant. This paper only discusses Particulate Matter monitoring stations, as it is the pollutant we are concerned by.

Different technologies have been developed to measure Particulate Matter. Amaral et al., 2015, have made an overview of the those. The figure 1.11, page 22, shows the different methods to measure PM concentration and size distribution. Olav Peeters, Scientific Coordinator at the Belgian Inter regional Environment Agency (IRCEL-CELINE), explained to me what kind of monitoring stations are used in Belgium to measure Particulate Matter measurement (see the interview page 74). This section is mostly based on the article of Amaral et al., 2015, Olav Peeters' interview and internet documentations.

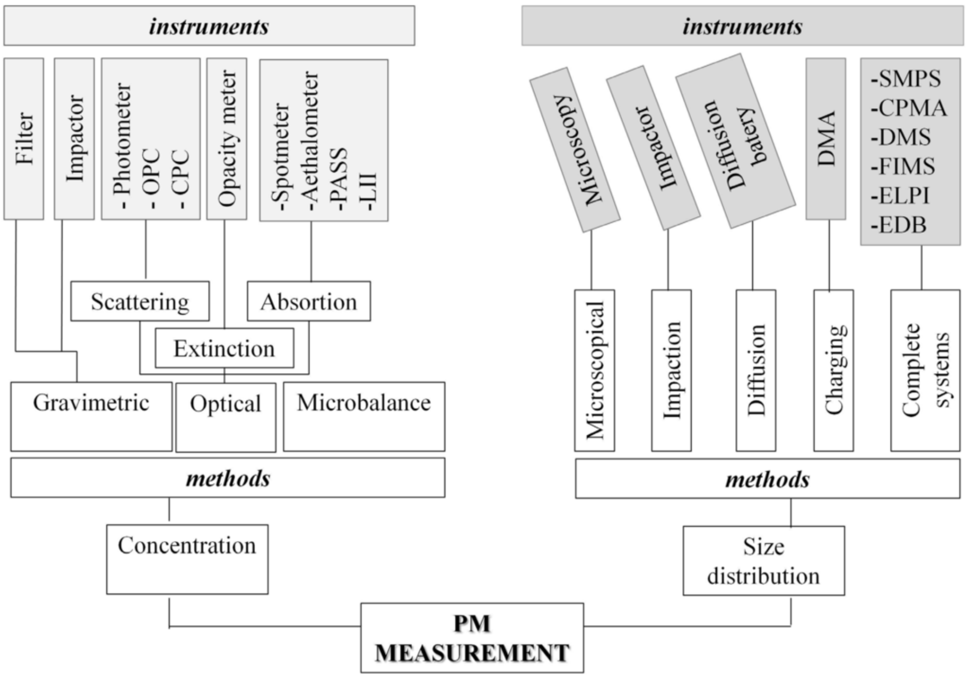

Figure 1.11: Methods and instruments for Particulate Matter measurement. Source: Amaral et al., 2015.

Three technologies are currently used in Belgium, optical, gravimetric, and microbalance methods (O. Peeters, Personnal interview, May 31, 2018).

Lets start first with the optical instruments. Wallonia uses the Grimm, while Flanders uses mostly the Fidas 200S, both are developed by German companies. Those optical instruments, as well as the SDS011, use the light scattering technology (O. Peeters, Personal interview, May 31, 2018). A light beam, usually coming from a light-emitting diode

(LED), lights the particles, which then reflect the light in all directions. Then, the scattered light is measured by photometer detectors. An algorithm converts the scattered light to a concentration of particles (Amaral et al., 2015). The density of the particles cannot be assumed to be constant, otherwise, the results would be far from reality (Palas, 2016). That is why optical sensors use an algorithm allowing them to fit the gravimetric sensor's measurements, which are more reliable (Z. Wang et al., 2016).

In addition to scattering, there are two other optical measurement methods, which are based on extinction and absorption of light (Amaral et al., 2015), but they are not described here as they are not used by low-cost sensor or official monitoring stations in Belgium.

Light scattering measurement makes continuous measurements possible, which enables the concentration of Particulate Matter to be known in real time. It also distinguishes different size classes: Each class gives the concentration of particles that are smaller or equal to a given diameter (Amaral et al., 2015). For example, the SDS011 can distinguish two size classes: 2.5 and 10 µm. Meanwhile, the Grimm has 30 classes. To know the different concentrations of the different size classes, the scattering optical machines do a light scattering size analysis. The advantage of the light-scattering technology is that it distinguishes between different size classes without using other devices than the LED and the photometer (Amaral et al., 2015).

Peeters explained that the Fidas is more reliable than the Grimm, the SDS011 should thus be compared to the former. Therefore, I focus on the Fidas in this thesis. The website of Palas, the company producing the Fidas, gives quite a lot of details on the machine.

As explained in section 1.2.2, humidity can skew the collected data when using scattered light technology. That is why the Fidas has "a drying line which prevents condensation from causing measurement errors" (Palas, 2016).

The second technology that is used by official monitoring stations is Belgium is the gravimetric method. Stations using a gravimetric technology are considered the reference ones by the European Commission. They are used to check if optical stations provide

Figure 1.12: The Fidas 200S developed by Palas, Germany, used in Flanders. Source: https://www.palas.de/en/product/fidas200s.

reliable data, and to calibrate them if necessary (Palas, 2016). The Sequential Sampler SEQ47/50 from Leckel is often used, but there are other gravimetric machines.

Figure 1.13: The Sequential Sampler SEQ47/50 from Leckel, used in Belgium. Source: http://www.leckel.de/index.php?option=com_content&task=view&id=24&Itemid=68&lang=en.

Amaral et al., 2015, explain that gravimetric instruments work with a filter that is weighted before and after the sampling period, the weight difference is thus the mass of Particulate Matter. To differentiate the different size classes, there are filters with different granulometric fractions, each filer then weights a different class. In order to avoid problems induced by temperature or humidity bias, the relative humidity and temperature are kept constant in the filters.

Usually, those samplers are used for daily averages (O. Peeters, personal communication, June 4, 2018). It is indeed impossible, with this technology, to get real time measurements, as it can provide concentrations every 15 minutes at most (Amaral et al., 2015).

Finally, the third technology used by official Particulate Matter monitoring stations in Belgium is the microbalance method. It is currently the best available technology. The microbalance monitoring stations, used in Brussels and Wallonia, are called TEOM-FDMS. It is one of the two microbalance methods (Amaral et al., 2015), the second one will not be described in this paper. TEOM stands for "Tapered Element Oscillating Microbalance" while FDMS stands for "Filter Dynamic Measurement System". The TEOM is the part of the station that actually makes measurements while the FDMS is the part that prepares the air for the measurement (O. Peeters, Personal interview, May 31, 2018). Amaral et al., 2015, say it is a well-established instrument to measure $PM_{2.5}$ and PM_{10} in real time.

The PM mass is measured by the TEOM via a filter in which the particles accumulate. The latter is connected to a tapered quartz wand whose resonance frequency is altered by the mass in the filter (Amaral et al., 2015). The more particles on the filter, the less resonance there is. Put it simply, it is a thrilling device that will thrill less and less with accumulation of particles in the filter. It is thus, like the gravimetric technology, directly linked to mass, which makes it more reliable than optical methods (O. Peeters, Personal interview, May 31, 2018).

Figure 1.14: The TEOM 1405F from ThermoFisher Scientific, used in Belgium. Source: https://assets.thermofisher.com/TFS-Assets/LSG/manuals/EPM-manual-1405F.pdf.

1.3.2 Measurements

These machines' accuracy has been extensively tested, and they all comply with many performance requirements (Palas, 2016; Thermo Fisher Scientific, 2016; Leckel, 2016). However, the optical instruments require calibration with gravimetric instruments (Z. Wang et al., 2016). And those gravimetric instruments themselves require calibration over time (O. Peeters, Personal interview, May 31, 2018), as it is also the case for TEOM (Midwest Research Institute, 1999).

The optical machines need those calibrations to provide reliable data, while the gravimetric and TEOM necessitate it over long periods to check if the measurements are still accurate. For example, the TEOM requires calibration every 6 months for the software, and every 2 years for the hardware. The calibration adjusts the distribution of the particles' density (see figure 1.15, page 28), or corrects an overall over or under estimation of the pollutant.

In addition, the TEOM-FDMS has been tested on the long term in the United Kingdom and in Germany (O. Peeters, Personal interview, May 31, 2018). During this test, they have observed a divergence of 60 percent between some instruments. This shows that even the best currently available technology can be wrong, and that Particulate Matter is something extremely hard to measure.

1.3.3 Models

Thanks to the monitoring stations deployed in Belgium, IRCELINE[1] (see more details about the organisation in section 2.1.4, page 43) makes two types of models to map Particulate Matter concentration in Belgium: assessment and forecast models (Belgian Interregional Environment Agency, n.d.). Both use interpolation techniques, which means they use mathematical methods to make a detailed map of air quality based on some measured points and other input data, detailed below. Those models are used for different things:

[1]Also referred as the "Belgian Inter regional Environment Agency"

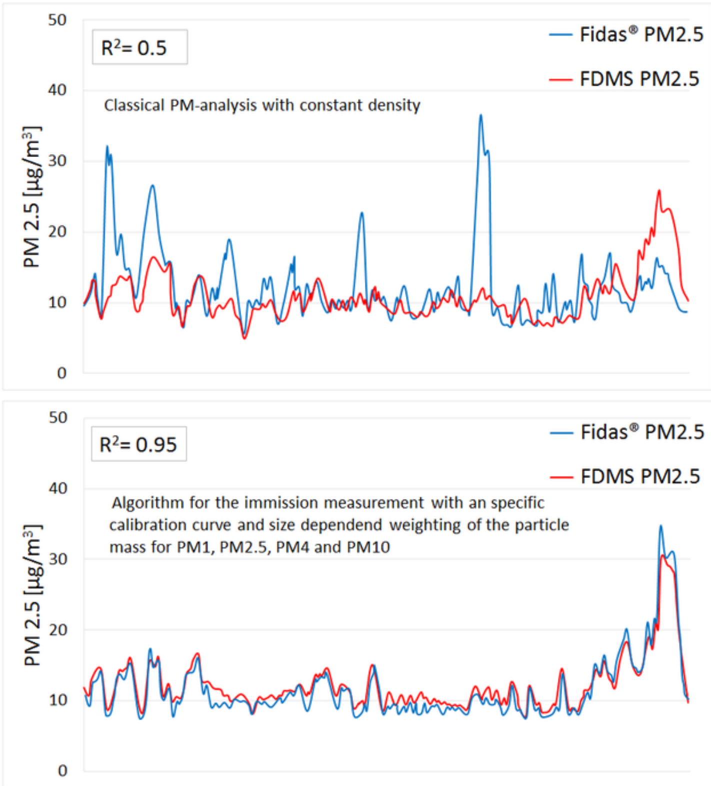

Figure 1.15: Comparison of the Fidas' measurements of $PM_{2.5}$ with the TEOM without and with calibration. Source: Palas, 2016.

- To decide with experts' opinion and the neighbouring countries' measurements when to issue SMOG alerts[1]
- The VMM (see section 2.1.3, page 41) uses it for its reports
- To make IRCELINE's annual reports
- To calculate population exposure
- To inform the public about current and forecasted air quality

They are however not used for European reports, but other usages of the models are planned for the future (O. Peeters, Personal communication, July 8, 2018).

The interpolation takes into consideration emission sources, meteorological conditions, chemical reactions in the atmosphere, and the way air pollution is transported in the air. In the modelling, emission sources are punctually represented. Concerning the weather, wind, rain, maritime air currents and temperature are taken into account to understand how pollution behaves. The reactions modeled reflects for example the fact that a lot of light induces the pollutants to form more ozone. Finally, the models take into account the pollution that goes in and out of the country (Belgian Interregional Environment Agency, n.d.).

The Chimere model is the basis of all the models used by IRCELINE. It has been developed by the "Laboratoire de Météorologie Dynamique" and the "Centre National d'Etudes Spatiales" in France. It is based on meteorological data and emission flows, thanks to those input data, the model calculates the concentration of pollutants in the atmosphere in high definition, from 1 to 100km resolution (Laboratoire de Météorologie Dynamique, 2000). It is then adapted by IRCELINE (O. Peeters, Personal interview, May 31, 2018). They use two assessment models, which are improved Chimere models, the RIO and the RIO-IFDM.

The RIO model, which has a mapping resolution of 4kmx4km, uses interpolation that takes into account the local aspect of pollution. It takes into consideration the fact that rural measurement points are representative of a vast area, while a measure point next

[1] In Flanders and in Brussels, when PM levels get above 50µg/m^3, speed is limited to 90km/h in 120km/h zones. Those alerts are mostly based on forecasts.

to a pollution emitter can only represent a small area. It then takes into account all the data IRCELINE has about land use in Belgium. In addition to the land use, the RIO model takes into account the Aerosol Optical Depth, which measures the reduction of sunlight caused by Particulate Matter (Belgian Interregional Environment Agency, n.d.; Earth Research System Laboratory, n.d.).

Then, the RIO-IFDM adds to the RIO model some meteorological data, like wind direction and speed, and puts them in relation with the emission points and lines, which location and emission levels are known. Those can be factory's chimneys and busy roads for example (O. Peeters, Personal interview, May 31, 2018; Belgian Interregional Environment Agency, n.d.).

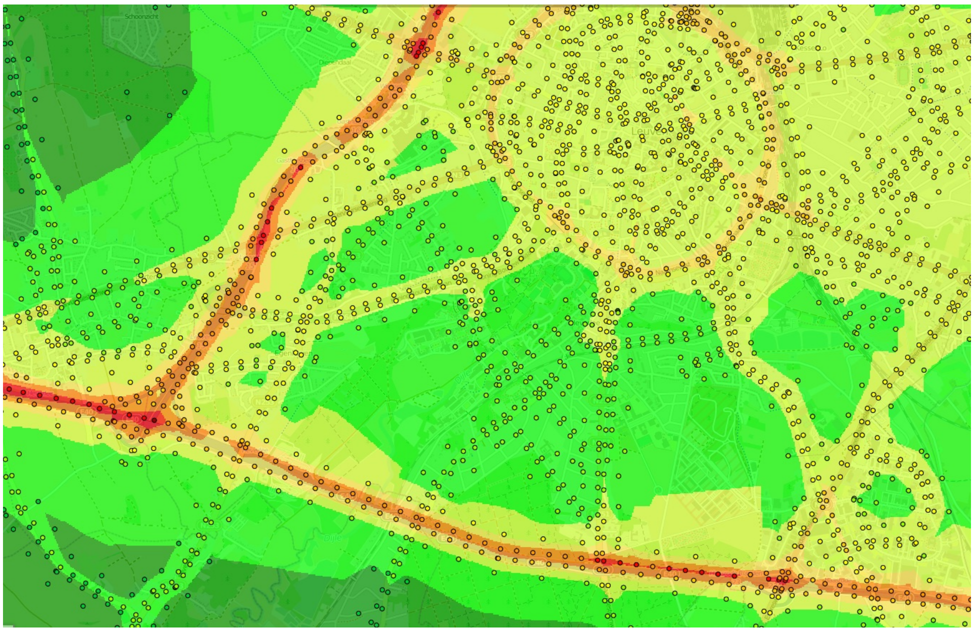

Figure 1.16: RIO-IFDM model around Leuven. Source: http://www.irceline.be/en/documentation/models/rio-ifdm.

IRCELINE is currently working on another model called the RIO-IFDM-OSPM, which will also take the street canyons into account. Those are street that form a hall because of the buildings along the street, so the pollution is trapped. The pollution concentrations in those places can thus increase. This needs to be modelled to make representations that will get closer to reality (O. Peeters, Personal interview, May 31, 2018).

The RIO-IFDM has been assessed to be reliable, and it is continuously improved, based on scientific research (Peeters, O. (31 May 2018), Personal interview). Although, it is clearly stated at the bottom of the maps built on those models that the data cannot be used for any research purpose.

Chapter 2

Public authorities and air quality in Belgium

In February 2018, a meeting took place with Brussels-Environment's representatives at Pascal Smets' office in Brussels. Then, a discussion about potential usage of the sensors for the public authorities was held. I realized that two things were missing for Brussels Environment to use the low-cost sensors:

1. There was a lack of a scientific evidence of the measurements' accuracy (see discussion on this matter in section 1.2.2, page 16).
2. We did not know enough the legislation they had to comply with, nor the institutions responsible of measuring air quality and taking decisions concerning air quality policies.

Within the federal state of Belgium, it can be difficult for the citizens to understand which institutions are responsible of air quality as it is affected by many sectors and industries. In addition, it is an international matter as the air and its pollution circulate between the countries. For this reason, the EU has made a directive called Air Quality Directive 2008/50/EC. The latter is discussed in section 1.1.1, page 5.

This chapter aims at answering the following two sub-research question: Who is responsible for air quality in Belgium and how do they operate ?

According to Vanhaeren et al., 2013, Belgium is lagging behind at three levels compared to its neighbouring countries concerning the mobilization of actors around health and environment.

1. Firstly, Belgium has not set up an institution network assessing the impact of air pollution on health. In addition to this, there are too few epidemiologists taking part in the social and political discussions. In general, health is not a dimension that is much discussed when addressing air pollution issues in Belgium.

2. Secondly, citizens associations are poorly represented in all air pollution related discussions.

3. And thirdly, the division of policy competences in Belgium makes it difficult to have a transversal approach regarding air quality, which has health, mobility and industrial dimensions. For example, mobility policies are mostly based on infrastructure development and neglecting health issue.

Vanhaeren et al., 2013, insist on the necessity of a transversal health-environment approach connecting every actor, for an efficient management of air pollution in Belgium. They also explain that Belgium has a multilevel organisation concerning air pollution. It means that there are different levels of authority working on this matter. This, in addition to the three holdups mentioned above, poses three challenges, say Vanhaeren et al., 2013.

1. The first one is that the competences related to air pollution are spread between different institution. Mobility itself is a policy competence shared by European, federal, regional and municipal institutions (Union Wallonne des Entreprises, cellule mobilité, 2018), as well as the industry. On the other hand, the environment is mostly a regional policy competence and health is a federal one (Vanhaeren et al., 2013). The dispersion of competences between different public authority levels is a serious obstacle making difficult coherent air quality policy making in Belgium.

2. Secondly, the structure of the institutions themselves does not foster collaboration between them. This has been shown via a survey among people working in the institutions dealing with air quality in Belgium (Vanhaeren et al., 2013).

3. Thirdly, they all have different aims, which makes it even more difficult to find agreements on decisions to take. This includes decisions related to possible new monitoring stations.

Understanding the complex political landscape regulating air quality issues is necessary to engage fruitfully in any action aiming at producing more integrated and transversal policy measures.

2.1 Regional level

In Belgium, environment, and thus air quality, falls under the responsibility of the three regions: Brussels-Capital, Wallonia and Flanders. The federal government is mainly putting up a coherent national plan.

The regions are responsible for two things concerning air quality: the pollution emitted by fix installations, and the network of air quality monitoring stations (Vanhaeren et al., 2013). To measure air quality, each region has set up its own station network, each being under the responsibility of a specific organisation:

- The "Institut scientifique de service public" (ISSeP) in Wallonia, with 23 monitoring stations. It collaborates with the AWAC (see page 39).
- The "Institut Bruxellois pour la Gestion de l'Environnement" (IBGE) in the region Brussels-Capital, with 12 monitoring stations.
- The "Vlaamse Milieumaatschappij" (VMM) in Flanders, with 69 monitoring stations.

Those organizations, in collaboration with other stakeholder, have two roles on their territory:

- Ensuring the continuous measurement of air quality
- Setting up plans and objectives to reduce air pollution

2.1.1 Brussels

The main institution responsible of air quality in Brussels is the "Institut Bruxellois de Gestion de l'Environnement" (IBGE). It was created in 1989 via a Royal decree. Its competences are, among others, to manage air quality and fight climate change (Institut Bruxellois pour la Gestion de l'Environnement, 2018). This institution comprises several action groups working together in order to define a transversal approach encompassing different environmental related dimensions. Their main objective is to promote a "sustainable urban integrated development" (Institut Bruxellois pour la Gestion de l'Environnement, 2015). To do so, they pursue four types of work/action:

- Administration work:
  - Drafting regulations and laws.
  - Providing administrative authorizations regarding environmental and energy matters (e.g environmental permit, necessary to operate some activities and/or institutions, Union Wallonne des Entreprises, 2018)
  - Control and inspect environmental matters
- Providing advice, support and awareness raising, in particulat the three following tasks:
  - Raise awareness and mobilize people and resources to achieve their environmental goals.
  - Advise people and organizations so they make sustainable and practicable choices.
  - Support and stimulate projects by providing financial and non-financial helps. The IBGE also develops projects on its own.
- Operational and field work, which mostly consists in developing and protecting green areas and watercourses.
- Collect and analyse scientific data, which concretely consists in data collection analysis and management, drafting reports, and plan environmental strategies.

Therefore, unlike the ISSeP, the IBGE is responsible for most of the tasks linked to air quality: deployment of new monitoring stations, analysis of the measurements, writing reports, raising awareness, etc. Their vision and program are defined every 5 years (Institut Bruxellois pour la Gestion de l'Environnement, 2015).

The IBGE is divided in several departments. In those, there are two units that we are particularly interested in:

1. The one that responsible for the network telemetry of air quality monitoring stations. This unit is based in the department "Environment quality and nature management", in the sub-division "Environment's quality". This is the sub-division to be contacted to learn about the monitoring stations, the data, the laboratory analysis, and other technical questions. It is also the unit that could test the low-cost sensor's accuracy (see section 3.1, page 44).

2. The unit "Information, general coordination, circular economy and sustainable city" and all its sub-units, which make different calls for projects, each targeting different people and organizations:

   (a) Municipalities and "Centres Publics d'Action Sociale"

   (b) Schools

   (c) Citizen groups

   (d) Businesses

   (e) Non-profit organizations

   The goal of those projects is to promote a more sustainable city via, among others, raising awareness. Consequently, this unit could be the one campaigning for the deployment of the low-cost sensors in Brussels.

To be transparent and engage in its mission, the IBGE writes different regional plans. In June 2016, it has adopted a document called "Plan Régional air-climat-énergie", which contains 64 measures and 144 concrete actions that aim at reducing Brussels' pollution emissions by 30% by 2025, compared to the emission levels of 1990. It contains 10 main axis, including "Buildings", "Transportation", "Renewable energies", "Urban planning" and "Air quality monitoring". Those measures are based on the "Code Bruxellois de l'Air, du Climat et de la maîtrise de l'Energie" (COBRACE), adopted in 2013.

The "Plan Régional air-climat-énergie" has draws four other regional plans:

- The "Plan régional de développement durable" (PRDD), which focuses on the development of housing, mobility and the economy for a sustainable city (Gouvernement Bruxellois, 2017.

- The "Plan Iris 2", which sets up objectives to develop a more sustainable mobility in Brussels (Institut Bruxellois pour la Gestion de l'Environnement, 2016).
- The emergency plan in case of pollution peak, which defines actions to take during nitrogen dioxide and PM_{10} peaks.
- The "Plan d'amélioration structurelle de la qualité de l'air et de lutte contre le réchauffement climatique", which aimed at meeting the air quality requirements defined by the EU and reducing the greenhouse gases emissions. This particular plan ended in 2010, since then new concrete objectives have been defined in order to achieve the main goals concerning air quality and greenhouse gases.

Those plans show that the region Brussels-Capital is willing to define objectives to improve air quality in many ways. For example, the Brussels government has defined in January 2018 Low Emission Zones (LEZ), where the heavily pollutant vehicle cannot circulate anymore (Bruxelles mobilité, 2018). The definition of those zones is defined in the "Plan Régional air-climat-énergie".

The "Plan Régional air-climat-énergie" from 2016 has an annex on air quality, containing information on pollution sources, the European norms, describing different pollutants, etc. This document states that 632 deaths per year could be avoided if the annual average of $PM_{2.5}$ was under 20µg/m^3. It also says that every monitoring stations' yearly average in the region Brussels- Capital exceeds this value. In addition, the European limitation of maximum 37 averaged days over 50µg/m^3 for PM_{10} was exceeded 59 times in 2013 by one of the stations. The annex also contains a graph (see below) showing the evolution of the sources of PM_{10} over time in the Region Brussels-Capital. This graph indicates that the focus to reduce Particulate Matter emissions should now be put on households and mobility.

The "Plan Régional air-climat-énergie" from 2016 also states that one of their goals is to raise awareness about the importance of clean air. In order to achieve this objective, public authorities want to display pollutant concentration in the streets, via a smartphone app, organize awareness campaigns, and training/information sessions to teachers and students about pollution and citizens' "power to act". The app was released in February 2018 and is usable and intuitive. The city of Brussels has also put some indicators in the city, notably at the crossroad of Art-Loi which is known to be very polluted as it is a

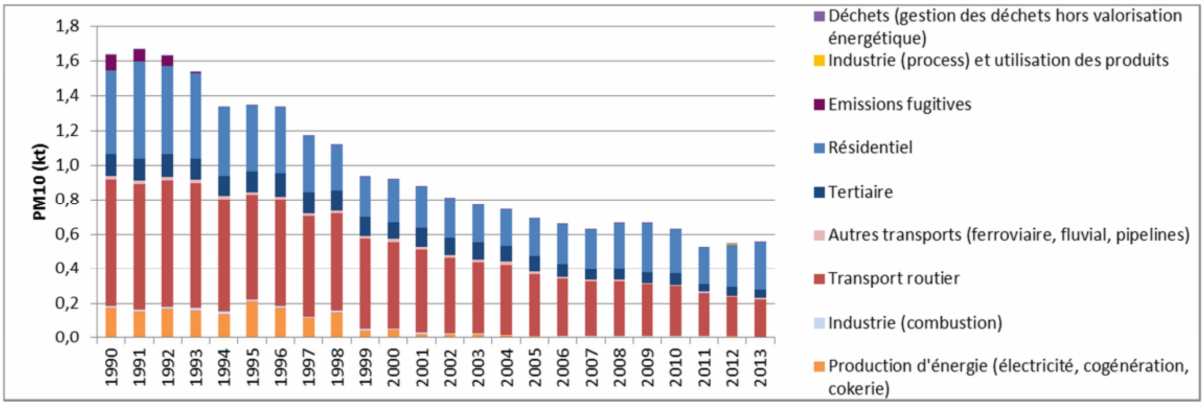

Figure 2.1: Evolution from 1990 to 2013 of PM_{10} in ktons per sector in the Region Brussels-Capital. Source: Institut Bruxellois pour la Gestion de l'Environnement, 2016.

very frequented street canyon. We can thus see that there is a real willingness to raise awareness among citizens.

In addition, the plan of 2016 has a whole axis about air quality monitoring. It explains that Brussels-Capital has 58 instruments spread between 12 monitoring stations. It also explains that there is in Brussels a Laboratory of Environmental Research, which works with IRCELINE on chemical analysis, modelling, and mathematical/statistical methods applied to air quality measurements and forecasts.

The plan also insists on actions to monitor indoor air quality, as Brussels inhabitants spend 80% of their time indoor. The "Cellule Régionale d'Intervention en Pollution Intérieure" is responsible for measuring indoor air pollution and its impact on health.

In contrast to what Vanhaeren et al. (2013) state, the IBGE seems to emphasize the importance of health institutions being involved in environmental issues. We can see it through two measures of the "Plan Régional air-climat-énergie": "develop and assure medical and scientific vigilance regarding air pollution's impact on health" and "sensitize and inform health and social professionals". The plan explains that it is important to know the risks of air pollution regarding health to provide alerts to citizens when necessary. To include health in the environmental matter, it states that collaborations between the federal, the regions and the communities have been established. Those collaborations aim at using developed tools used by institutions such as the World Health Organization

(WHO) to improve our knowledge of pollution exposition's impact on health. Unfortunately, the plan does not explain those collaborations in detail. Three actions are stated to accomplish the two measures above. The first one is to develop research, in collaboration with universities and companies. The second action is to develop pollutant's concentrations not to overcome for indoor pollutants. And the third action is to promote formations that integrate the air pollution problematic. This action does not give concrete examples if not for indoor air quality. We can note those three actions mostly focus on indoor air quality and do not give much concrete information about what is planned to be done.

2.1.2 Wallonia

In Wallonia, three organizations are directly working on air quality:

1. The "Institut Scientifique de Service Public" (ISSeP)
2. The "Cellule permanente Environnement-Santé" (CPES)
3. The "Agence Wallonne de l'air et du climat" (AWAC)

The ISSeP deals with the technical and scientific side of air quality monitoring. That essentially means maintaining official monitoring stations and securing the measurements' accuracy. They are totally independent in the way they work (G. Gérard, Personal interview, June 13, 2018).

The ISSeP was created by a decree in 1990, which states in detail its competences, i.e. soil and mineral resources, combustibles and energy processes, pollutants and decontamination, risk management concerning the environment linked to industrial zones. Its mission consists in exploiting the Walloon network of pollution monitoring systems (immissions and emissions), the laboratory analyzing air, water and waste, conducting technological research, etc. It works under the authority of the government. The government provides a triennial strategy that is reviewed every year.

In addition, a Walloon government decree, issued in 2010, describes with less details the scope of competences of the public organizations related to air quality in Wallonia. The four main tasks of the ISSeP are:

- Ensuring the proper functioning of the air quality monitoring stations

- Checking the accuracy of the measurements, congruent with the EU standards
- Making technical investigations before the deployment of new monitoring stations
- Participating in the European programs related to air quality, supported by the European commission

The ISSeP works in close collaboration with the "Cellule permanente Environnement-Santé" (CPES), which was created via a cooperation agreement in 2003 (G. Gérard, Personal interview, June 13, 2018). Its role is to make the link between Walloon institutions and citizens on topics related to the environment and health. It notably answers every question coming from the citizens on this matter.

The Walloon government has written the "Programme d'actions régionales environnement-santé" (PARES), which is meant to be executed by the CPES. The programme's goal is to define objectives for all Walloon institutions working in the field of the environment. The PARES is comparable to the "Plan Régional air-climat-énergie" in Brussels, it defines objectives that should be achieved via concrete actions. However, the PARES is less ambitious than the Plan made by the IBGE. It contains 7 measures declined in 20 actions. It essentially focuses on the measures and their related actions. The PARES was planned for 2008-2013, and there has not been any other text since. However, the CPES is currently working on it and they want to publish it by the end of 2018 (CPES desk, personal communication, June 25, 2018).

It is important to underline that the PARES's and CPES's main objective is to raise awareness about pollution and its effect on health (Gouvernement Wallon, 2008). It is one of the major aim of Influencair, therefore, collaboration with the CPES could be interesting.

The third institution is the "Agence Wallonne de l'air et du climat" (AWAC). It takes care of the administrative and legal tasks, and its competences, defined in the decree of 2010, are:

- Evaluating ambient air quality
- Defining where to measure air quality, action programs and data exploitation
- Assessing and forecasting the atmospheric emissions

- Making an evaluation report of the monitoring stations' measurements, based on the technical assessment made by ISSeP
- Making an annual report about air quality measurements
- Executing plans to reduce ambient air pollution. If necessary, this can be done in collaboration with the regional institutions mentioned in this chapter, other states and the European commission, if the levels of pollution overcome the European limitations or other target value
- Coordinating the plans in the Walloon territory aiming at reducing ambient air pollution

The ISSeP provides the data of the monitoring stations to the AWAC which then makes reduction plans, decides of new monitoring stations to install, etc. If there is not enough monitoring stations in urban areas to get a representative picture of the pollution, the decree states that the AWAC has to make measurement campaigns using mobile stations (G. Gérard, Personal interview, June 13, 2018). The ISSeP developed a model that is different from the one used by IRCELINE, defined in section 1.3.3.

2.1.3 Flanders

The institution responsible of air quality monitoring in Flanders is the Vlaamse Milieumaatschappij (VMM). The VMM "is an agency of the Flemish government working towards a better environment in Flanders". It works on three domains: water, air and the environment. Like ISSeP and the IBGE, its scope of action is limited to its territory (E. Elst, Personal interview, June 25, 2018).

Concerning air quality, the VMM is responsible for:

- Measuring air pollution via the official monitoring stations on the Flemish territory
- Forecasting peaks of PM and Ozone
- Writing reports about the state of the environment in Flanders. Those reports are then used by the Flemish government to make environmental policies

- Advising the minister for Environment, Nature, Spatial Planning and Agriculture

The air quality policies are made by the Flemish government. The person of reference among the latter is the Flemish Minister for Environment, Nature, Spatial Planning and Agriculture. The minister works with the administration of the Environment, Nature and Energy which helps her making the right policies. The VMM is part of this administration, consequently, it collaborates directly with her and the government. The VMM also contributes to the implementation of air framework directives in the Flemish legislation (Flanders Environment Agency, 2018).

To improve the environment, the VMM also works in close collaboration with:

- Flemish provinces,
- Cities and municipalities,
- The Flemish Welfare and Health Agency,
- The Flemish ministry of Transport and Public, Works,
- and more.

It also works with foreign institutions and organizations. It helps defining European directives by bringing its expertise. In addition, it collaborates with neighbouring countries to address cross-national issues such as water and air pollution.

The VMM writes three types of reports:

1. A yearly report about the state of the environment in Flanders
2. The reporting towards the European commission, in collaboration with IRCELINE
3. Shorter reports about different environmental topics (energy, biodiversity, water, etc.)

The VMM is also interested in the low-cost sensors. Evelyn is responsible of a project called LIFE VAQUUMS, whose goal is to assess the use of low-cost sensors to measure air quality at local or regional levels. The project which has just started reflects a will to develop its usage on a bigger scale.

2.1.4 IRCELINE

The cooperation between the Belgian regions is limited to a Cooperation Agreement, made in 1994, which led to a unique network of air quality monitoring. It was concretely established via the creation of an inter regional institute, called IRCELINE. The scope of IRCELINE's competence is clearly stated in the Cooperation Agreement. The latter explains that IRCELINE's main goal is to develop a scientific approach to air quality measurement and data interpretation, on the whole territory of Belgium.

IRCELINE is responsible of:

- Providing continuous forecast, including Smog alerts.
- Informing the public on air quality in real-time and via assessments.
- Delivering national reports to the European authorities.
- Establishing a common scientific basis between monitoring networks.
- The Inter regional calibration laboratory.
- The Inter regional data processing centre, responsible for the real-time aggregation of the data about air quality.

The models they work on have been detailed in section 1.3.3, page 27. IRCELINE is well known among the different organizations working on air quality in Belgium (Vanhaeren et al., 2013).

Chapter 3

What usage of the low-cost sensors in Belgium

This chapter will aim at answering the sub-research question: How can public authorities benefit from citizen-driven air quality measurements?

3.1 Accuracy test

As is has been explained in section 1.2.2 (page 16), there are three clues that the sensors could provide correct measurements:

- The correlation observed between the monitoring stations and the citizen sensors on a national level, see figure 1.8, page 18.
- The correlation between a citizen sensor and a monitoring station on a local level, see figure 1.9, page 18.
- The test that has been made by the National Dutch Institute for Public Health and the Environment, between citizen sensors and monitoring stations around Amsterdam, see figure 1.10, page 19.

However, we also know that the sensors provide inaccurate data in very dry and humid conditions. Therefore, as it has been said in section 1.2.2 and at the beginning of chapter

2, it is necessary to make an in-depth analysis of the sensor's accuracy before using it for another purpose than raising awareness.

In this section, a method to assess the accuracy of the SDS011's measurements will be suggested, based on Castell et al., 2017, Spinelle et al., 2015, and the European Commission, 2010. The methodology defined by the European Commission is the official one, needed to test the equivalence of air quality monitoring stations. This section contains more details than in Castell et al., 2017 and Spinelle et al., 2015, but less than in European Commission, 2010.

3.1.1 Data Collection

Castell et al., 2017, tested the AQMesh sensor, which is produced in the UK. It also uses the optical scattering technology (defined in section 1.3.1, page 26) to measure PM_{10} and $PM_{2.5}$. To assess the accuracy of this low-cost sensor, they have co-located 24 AQMesh, spread next to 4 monitoring stations over a period of 6 months in different places in Oslo, Norway. As the SDS011 uses the same technology, it seems reasonable to test it with the same method.

To apply this test to the SDS011 in Belgium, I recommend putting the sensors in different monitoring stations in Flanders. As explained in section 1.3.1, Flanders only uses the Fidas S200 machines, which have been tested with gravimetric stations, using the EU reference technology. Testing the SDS011 with only Fidas stations would avoid accuracy variance between the reference stations. In addition, as it has been discussed in section 1.3.1, page 26, the Fidas machines are more reliable than the other optical stations used in Belgium.

However, in contrast to Castell et al., 2017, it is necessary to co-locate the low-cost sensors with monitoring stations not only in urban areas. As people are exposed to air pollution in the countryside, near the coast, and in cities, it would be interesting to test the sensors' difference of accuracy between those areas. Here is a list of locations, equipped with Fidas S200, that would include the different areas:

- Moerkerke, to assess the accuracy of the SDS011 in an area exposed to coastal meteorological conditions.

- Antwerp ring, to test the sensor in an open area with high exposure to traffic.
- Aarschot, for rural inner land testing.
- Center Antwerp (Belgiëlei), for narrow street urban testing.

The inconvenient of the SDS011 compared to the AQMesh is that it needs to be in the range of a 2.4GHz WiFi router, it should also be near an electricity socket. As explained in section 1.2.1, a LoRaWAN SDS011 sensor, which does not need to be connected to a WiFi, is being developed, but it is not ready yet. Thus, if the WiFi is not available in the four stations above, other places to conduct the co-location tests should be found.

It would be interesting to measure the traffic as well as the meteorological conditions, that way it will be possible to know where deviations between the low-cost sensors and the monitoring stations could come from. The measurements from the latter can be easily pulled from the open API (Application Programming Interface) of IRCELINE. A reference humidity sensor is also necessary to check that the DHT022 (described in section 1.2.1) also provide good measurements. Fortunately, the Fidas stations also measures temperature, pressure and relative humidity. The DHT022 also displays relative humidity, which is "the amount of water that is present in the air compared to the greatest amount it would be possible for the air to hold at that temperature" (Cambridge Dictionary, 2018). It is convenient that they both use relative humidity, that way the data collected will not need much manipulation to compare them.

3.1.2 Data Analysis

When the data is collected, the first thing to calculate is the Between-sampler/instrument uncertainty u_{bs}^2 (formula 3.1) for each location.

$$u_{bs}^2 = \frac{\sum_{i=1}^{n}(y_{i,1} - y_{i,2})^2}{2n} \tag{3.1}$$

where

$y_{i,1}$ is the 24-hour average of the 6 sensors' measurement on day i;

$y_{i,2}$ is the 24-hour average of the monitoring station's measurement on day i;

n is the number of days of results.

If the Between-sampler/instrument uncertainty is $\leq 2.5\mu g/m^3$, both instruments are considered equivalent.

Then, to go deeper in the analysis and know if the sensors meet the Data Quality Objectives, a regression between the monitoring station and the sensors is to be calibrated. A regression is a statistical process that estimates the relation between two variables, in this case, the low-cost sensors' and the monitoring stations' measurements. It will be followed by the calculus of the Relative Expanded Uncertainty, detailed below.

Spinelle et al., 2015, and Castell et al., 2017, explain that we can either make a simple linear regression, a multivariate linear regression, or an artificial neural network. Focus will be set on the simple linear regression as Burke, 2001, explains that it is the most commonly used one to compare measurement instruments. Plus, it is the type of regression recommended by the European Commission, 2010. It is also the method that has been followed by the National Dutch Institute for Public Health and the Environment for testing the SDS011[1] (see section 1.2.2). A simple linear regression, as defined by the Department of Statistics Online Programs, 2018, is a "statistical method that allows us to summarize and study relationships between two variables". It is formulated as Y=aX+b, where Y is the the response variable and X is the predictor variable.

To make a regression, Podgórski, 2017, explains that the data set needs to be divided into a training set that is used to build the regression, and a validation set, that assesses the built model. In the application by Castell et al., 2017, they used the first two weeks of data to calibrate the regression, and the rest to validate it.

To build the linear regression, Spinelle et al., 2015, explain that they used sensors' responses as predictor variable and the reference measurements as the response variable. The predictor variable is the one that is used to predict the response variable, which behavior is being explained in term of the predictor variable. They formulated it as: Y=aX+b, where Y is the quantity of PM measured by the AQMesh, and X is the measurement of the monitoring station in the same location at the same moment. The data used by Castell et al., 2017, was aggregated by hourly means. They followed the method of minimization of the residual sum of squares (RSS) to get the parameters a and b of

[1] As a reminder, this analysis has been very limited, in term of depth as well as quantity of data. Contact has been made with Joost Wesseling but no interview took place.

the regression. This method builds a linear regression that minimizes the deviation of the data points from the linear regression. The formulas 3.2 and 3.3 show how the parameters are obtained.

$$a = \frac{n\sum_{i=1}^{n} x_i y_i - (\sum_{i=1}^{n} x_i)(\sum_{i=1}^{n} y_i)}{n\sum_{i=1}^{n} x_i^2 - (\sum_{i=1}^{n} x_i)^2} \tag{3.2}$$

$$b = \frac{(\sum_{i=1}^{n} y_i) - a\sum_{i=1}^{n} x_i}{n} \tag{3.3}$$

Where:

x_i is the hourly averaged monitoring station's measurement during time i;

y_i is the hourly averaged sensors measurements during time i;

n is the number of hours during which measurements took place.

Eventually, after averaging the measurements, one dataset should be obtained, which should look like in table 3.1 below, where :

- "TimeAndDate" represents the time when the sensors' measurements have been averaged[1];
- "AvgSensor25" represents the averaged amount of $PM_{2.5}$ measured by the 6 sensors in "Location" during "TimeAnDate", in µg/m^3;
- "Station25" represents the amount of $PM_{2.5}$ measured by the monitoring station in "Location" during "Time&date", in µg/m^3;
- "AvgSensor10" represents the averaged amount of PM_{10} measured by the 6 sensors in "Location" during "TimeAndDate", in µg/m^3;
- "Station10" represents the amount of PM_{10} measured by the monitoring station in "Location" during "TimeAndDate", in µg/m^3;
- "Location" represents the place where the measurement took place: Moerkerke; Aarschot; Antwerp (Ring); Antwerp (Center).

With such database, it are able to build 8 different regressions, as showed in table 3.2 below.

[1] This shows what the dataset would look like if the experiment had started on the 1st October 2018

TimeAndDate	**AvgSensor25**	**Station25**	**AvgSensor10**	**Station10**	**Location**
"2018-10-01 00:00:00"	12	15	20	22	Moerkerke
"2018-10-01 00:01:00"	15	20	24	24	Moerkerke
"2018-10-01 00:02:00"	17	17	21	27	Moerkerke
"2018-10-01 00:03:00"	24	21	40	44	Moerkerke
...	...	...	...		
"2018-10-01 00:00:00"	10	15	20	22	Aarschot
"2018-10-01 00:01:00"	12	12	23	24	Aarschot
"2018-10-01 00:02:00"	16	18	35	31	Aarschot
"2018-10-01 00:03:00"	20	15	21	24	Aarschot
...	...	...	...		

Table 3.1: Dataset example - Averaged measurements at a certain place and time.

Location \ PM	2.5	10
Moerkerke	**AvgSensor25 = a_1 Station25 + b_1 Where Location = 'Moerkerke'**	**AvgSensor10 = a_5 Station10 + b_5 Where Location = 'Moerkerke'**
AntwerpRing	**AvgSensor25 = a_2 Station25 + b_2 Where Location = 'AntwerpRing'**	**AvgSensor10 = a_6 Station10 + b_6 Where Location = 'AntwerpRing'**
Aarschot	**AvgSensor25 = a_3 Station25 + b_3 Where Location = 'Aarschot'**	**AvgSensor10= a_7 Station10 + b_7 Where Location = 'Aarschot'**
AntwerpCenter	**AvgSensor25 = a_4 Station25 + b_4 Where Location = 'AntwerpCenter'**	**AvgSensor10 = a_8 Station10 + b_8 Where Location = 'AntwerpCenter'**

Table 3.2: Regressions - Regressions depending on the place and pollutant, see table 3.1 above for the metadata.

Each regression allows us to calculate a Relative Expanded Uncertainty (REU), which defines the uncertainty of the tested sensors compared to the monitoring station with which it has been co-located, for each kind of PM and in different weather conditions. The Data Quality Objectives (DQO) defined by the Air Quality Directive (2008/50/EC)[1] explains that the REU of an instrument compared to a reference one should not exceed 25% for PM_{10} and $PM_{2.5}$. Therefore, if the REU is inferior to 25%, the sensors can be regarded as equivalent to the reference device, which would be the Fidas 200S in our case. If it is superior to 25%, it will not be considered equivalent (European Commission, 2010).

The formula 3.4 shows how to calculate the Expanded Relative Uncertainty based on a regression. 8 different REU should be produced as there are 8 different regressions. In addition, the European Commission, 2010, explains that the regression and the REU should also be done on the whole dataset, without classification by location, as well as on some sub-datasets.

$$U_r(y_i) = \frac{2(\frac{RSS}{(n-2)} - u^2(x_i) + (b_0 + (b_1 - 1)x_i)^2)^{1/2}}{y_i} \tag{3.4}$$

Where:

y_i= 50 µg/m^3 for PM_{10} or 30 µg/m^3 for $PM_{2.5}$;

x_i is the value corresponding to y_i found via the simple linear regression:

$y_i = b_1 + x_i * b_0$;

$u^2(x_i)$ is the uncertainty of the reference instrument for x_i corresponding. $u^2(x_i)$ can be assumed to equal $0.64(\mu g/m^3)^2$ (European Commission, 2010);

b_0 and b_1 are respectively the slope and the intercept of the simple linear regression;

RSS is the Residual Sum of Square of the regression (formula 3.5);

n is the number of observations.

$$RSS = \sum_{i=1}^{n}(y_i - b_0 - b_1 x_1)^2 \tag{3.5}$$

[1]For more information, this directive has been discussed in detail in sections 1.1.1, 5, and 2.1.1, page 34.

Formula 3.4 is not demonstrated in the articles mentioned above. It will thus be taken as it is.

Figure 3.1 below shows one year co-location's results of the Fidas 200S with the LVS3, which is a gravimetric Particulate Matter monitoring station. Such table would be the final results of the assessment.

This analysis would be a good overall indicator of the SDS011's accuracy, however, it is also important to make additional investigations with the collected data:

- Measurements' variation between the sensors
- Levels of humidity above and under which the data gets skewed (very dry and very wet conditions)
- Accuracy depending on the meteorological conditions
- Accuracy depending on the pollution level

It is already known that the measurements are biased on rainy days. Therefore, those additional investigations would indicate when to not take the data into account, which could lead to an improvement of the overall measurements' accuracy[1]. Defining when the data should be dropped should be done before building the regressions and calculating the REU. However, the Air Quality Directive (2008/50/EC) requires a minimum data capture of 90%, which means that the amount of data that can be dropped is limited.

The results of such analysis could then assess if the sensors could suit official measurements, research, improving IRCELINE's models (see page 27) or if they should only be used to raise awareness among citizens. Scenarios about the different possibilities have been developed in section 3.2.1, page 55.

It is also possible to test the sensors' accuracy in a laboratory. Such analysis could be lead by the public laboratories mentioned in chapter 2. However, it is better to test the sensors on the field because the weather, which can hardly be simulated in a laboratory, has a big influence on the measurements' accuracy (Y. Wang et al., 2015).

[1]Those tests' methodologies are not detailed here, but they should be done if the resources are available.

All comparisons $PM_{2.5}$ (with applied slope & offset correction)		
number of value pairs	225	
uncertainty between Fidas® test devices	0.44 µg/m^3	(allowed: 2.5 µg/m^3)
uncertainty between the reference measurement devices	0.58 µg/m^3	(allowed: 2.5 µg/m^3)
slope b	0.999	
intercept a	0.012	
expanded measurement uncertainty W_{CM}	**10.17%**	**(allowed: 25 %)**

All comparisons PM_{10} (with applied slope & offset correction)		
number of value pairs	227	
uncertainty between Fidas® test devices	0.64 µg/m^3	(allowed: 2.5 µg/m^3)
uncertainty between the reference measurement devices	0.62 µg/m^3	(allowed: 2.5 µg/m^3)
slope b	0.999	
intercept a	0.015	
expanded measurement uncertainty W_{CM}	**7.22%**	**(allowed: 25 %)**

Figure 3.1: Results of a suitability test between the Palas Fidas 200S and the LVS3. Source: The suitability-tested immission measurement system for online and simultaneous $PM_{2.5}$ and PM_{10} measurements, Palas.

The method to do it will not be detailed here, but it is important to know that this alternative is possible. It could also be done in addition to the field testing above for further analysis of the SDS011.

3.2 Use by public institutions

As stated at the beginning of chapter 2, the accuracy of the sensors has to be first assessed before it could be used by public institutions. In addition, understanding who is responsible of what is also important to understand which institution would be interested by the low-cost sensors, and why.

The VUB is currently doing a research to understand if building and setting up a low-cost air quality sensor at home raises the builder's awareness about air pollution, and leads to personal behavioral changes that produce less air pollution (Laura Temmerman[1], Personal communication, July 6, 2018). The study is done in four steps:

1. They conduct a survey among citizens who are about to build their sensor. The questions aim at grasping each participants' awareness and behaviors towards air pollution.
2. The participants build their sensor and set it up at their place.
3. A month after the workshop, they fill another survey that assesses a second time their awareness and behavior.
4. Conclusions are drawn from the comparison between the first and the second survey.

The research is done on a sample of 30 individuals. This number is too low to induce that the results are applicable to everyone building and setting up a low-cost sensor. In statistics, inducing means generalizing conclusions for a population, based on a sample of the latter (Dictionary.com, 2018). Figure 3.2 below gives the sample size required to induce conclusions from a sample to a given population, which depends on the chosen confidence level and margin of error. The margin of error is "the deviation between the respondents' opinions and the entire population's opinion", and the confidence level is the probability that the population falls within the margin of error [2].

[1]Laura Temmerman is a junior researcher of the VUB/IMEC working on the project Hack'Air.

[2]Those matters will not be discussed in more detail here as it gets out of the paper's scope. Refer-

	Confidence level = 95%			Confidence level = 99%		
	Margin of error			Margin of error		
Population size	5%	2,5%	1%	5%	2,5%	1%
100	80	94	99	87	96	99
500	217	377	475	285	421	485
1.000	278	606	906	399	727	943
10.000	370	1.332	4.899	622	2.098	6.239
100.000	383	1.513	8.762	659	2.585	14.227
500.000	384	1.532	9.423	663	2.640	16.055
1.000.000	384	1.534	9.512	663	2.647	16.317

Figure 3.2: Minimum sample size to induce conclusion to a given population, confidence level and margin of error. Source: https://tinyurl.com/y8338cgy

However, even with a small sample, it can provide an idea of the possible impact on awareness and behavior. If the study finds out that building and setting up a sensor actually raised awareness and changed behaviors for the study's participants, it could be a motivation for public institutions to spread the low-cost air quality sensors. Awareness is necessary for people to realize the impact of their life habits on their own health, and to act knowingly. The results of the research should be available by the end of summer 2018.

Two things need to be known for public institutions to consider exploiting the low-cost sensors:

1. Its accuracy (method described in section 3.1)
2. Its impact on awareness and behavioral change (VUB's research exposed above)

The following subsection explains the sensors' potential depending on their accuracy and impact on awareness and behavior, formulated in the shape of scenarios. The impact on awareness and behavior will not be distinguished to avoid unnecessary complications. Also, the categories have been grouped by accuracy levels because it is the most important determinant of its possible use. Indeed, providing measurements that are as close to the reality as possible is important to avoid drawing improper conclusions, and giving false information to the public.

ences about confidence intervals and margin of error: https://www.youtube.com/watch?v=hlM7zdf7zwU; https://www.checkmarket.com/blog/how-to-estimate-your-population-and-survey-sample-size/

3.2.1 Scenarios and possible use

The diagram 3.3, page 56, summarizes the possible actions depending on the scenarios developed in this subsection.

Low accuracy

If the difference between the low-cost sensors' measurements and the monitoring station ones is too large, the sensors' data should not be used as it would provide misleading information. This situations is defined here as if the Expanded Relative Uncertainty would be greater or equal to 50%[1].

If the VUB's research shows that there was no impact on people's awareness and behavior, the SDS011's usage can fairly be given up. It could teach people technology and sensitize them about open data. However, those benefits are too restrained compared to the mobilized resources.

On the other hand, if it does raise awareness and/or changes behavior, it could be interesting to spread the sensors via a workshop like defined in section 1.2.3, page 20. The map displaying the sensors' measurements would state that they are skewed, and redirect people to IRCELINE's website and its official measurements. An interesting alternative would be to correct the sensors' data thanks to the measurements provided by the monitoring stations. This correction can be done via a weighted average in favor of the monitoring station closest to each sensor, as in formula 3.6 below. It could also be corrected in more detail thanks to the models defined in section 1.3.3, page 27.

$$C_i = w * x_{MS_i} + (1 - w) * x_{LC_i} \tag{3.6}$$

[1]This number, as well as the following ones, have been chosen arbitrarily, based on the Expanded Relative Uncertainty necessary to meet the DQO.

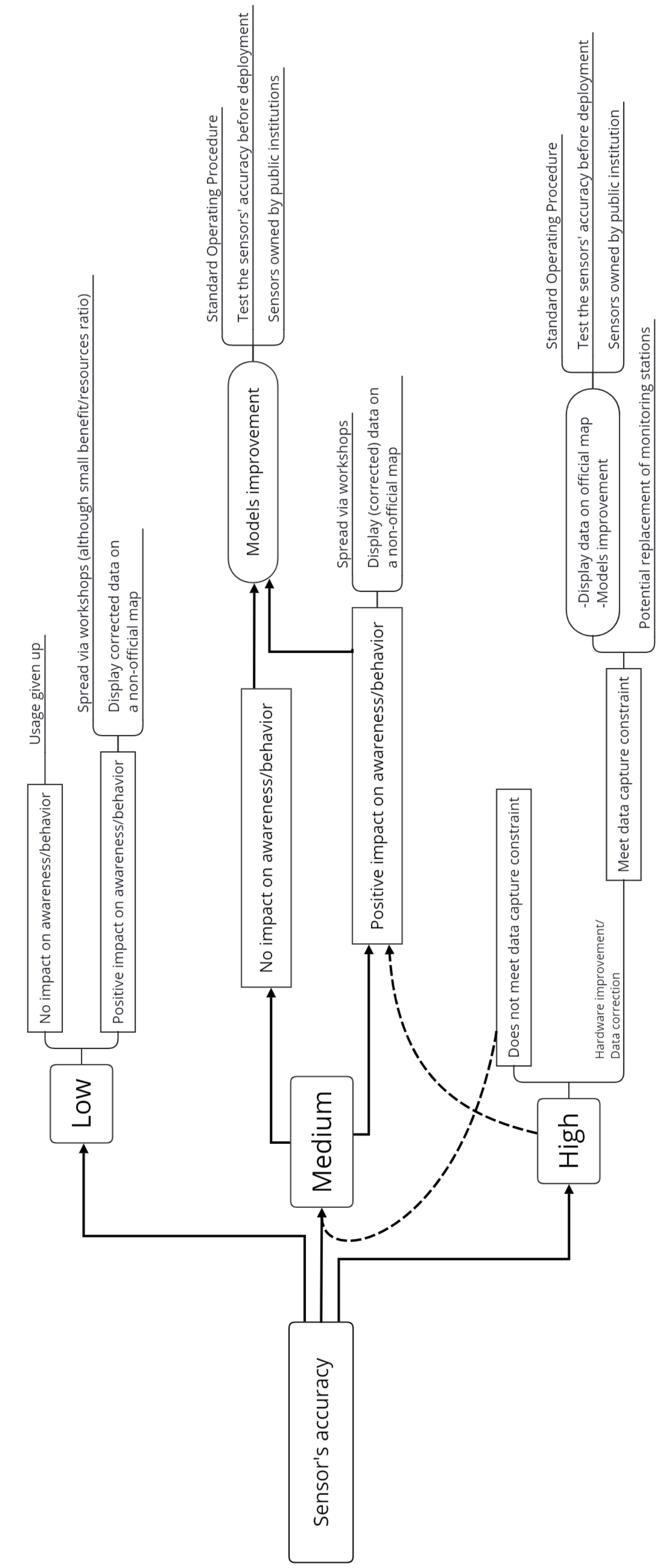

Figure 3.3: Summary diagram of the scenarios and potential actions according to them.

Where:

x_{LC_i} is the measurement of the low-cost sensor i;

x_{MS_i} is the measurement of the monitoring station which is closest to sensor i;

C_i is the corrected measurement of the low-cost sensor i;

w is the weight of the correction where $w \in]0.5; 1[$.

However, displaying corrected data that could be far from the reality is very dangerous. In addition, the resources to mobilize seem disproportionate compared to what it would achieve. The SDS011 use could fairly be renounced and alternatives could be found to raise awareness about air pollution and its impact on health. Other low-cost sensors' accuracy could also be tested.

Medium accuracy

This is the situation in which the SDS011 does not meet the DQO, but still gets a good handle of air pollution. This situations will be assumed if the Expanded Relative Uncertainty $U_r(y_i) \in]0.25; 0.50[$.

The measurements could be displayed on a non-official map without correction, or with a correction as proposed in equation 3.6 with a smaller weight w than in the previously. Displaying IRCELINE's measurements in addition to the low-cost sensors ones would be an interesting solution. It is again important to specify that the sensors' measurements could be faulty, and that the users should always compare their measurements with the monitoring station ones.

In this situation, the measurements cannot be displayed on official maps as the low-cost sensors do not meet the DQO. They cannot be used for European reporting neither. However, it could still be used to improve the models defined in section 1.3.3, page 27. As a reminder, those models map air pollution on a 4kmx4km and 1kmx1km resolution, based on the inputs provided by the monitoring stations. More measurement points would improve them which would thus give a more accurate assessment of the reality, including population exposure. Improving the models is important as they are used to communicate air quality to the population and to write national and Flemish reports. Nevertheless, the quality of the data necessary as well as its possible correction should be discussed further before such use.

For the sensor's data to be usable for the models, the deployment should be done with a Standard Operating Procedure (O. Peeters, Personal interview, May 31, 2018). Its goal is to describe the sensor's deployment into a step-by-step process that can then be used for every sensor (Morris, 2008). The goal is to deploy them in a way that makes their data comparable with each other, e.g. putting them all on the street side of the first floor, making sure they are connected to a functional WiFi network, avoiding places exposed to marginal pollution such as cigarettes smoke, etc. It would also be valuable to gather data about the location and the surroundings of the sensor, if it is located in a street canyon for example.

Each sensor's accuracy should ideally be tested next to a monitoring station before deploying it independently. One week seems a reasonable length to be sure the sensor does not provide skewed measurements. There has been cases of dysfunctional sensors, therefore, testing before deploying them would avoid possible losses of time to fix or replace them.

The low-cost sensors could then be valuable even if they do not have a positive impact on awareness or behavior. Therefore, a possibility that has not been mentioned yet, it that they could be owned by public institutions. This would avoid organizing workshops for citizens to build and set it up. Besides the resources it would save, the public institutions could be sure it is installed according to the Standard Operating Procedure. Nevertheless, it would be valuable to organize such workshops and to involve citizens if this would lead to an improved awareness and behavior changes. This matter should also be discussed with people working on the models, to know if sensors owned by citizens could also be used to improve the latter.

High accuracy

A situation of high accuracy of the low-cost sensors is assumed if their Expended Relative Uncertainty $U_r(y_i) \leq 25\%$. In addition, a minimum data capture of 90% is necessary[1] to meet the DQO. This constraint has not been mentioned yet as the Expended Relative Uncertainty constraint was not met in the previous scenarios.

[1]This means measurements should be made on at least 0.9*365=329 days of the year.

It has been discussed in section 1.2.2, page 16, that the SDS011 provides inaccurate measurements during high humidity periods. This can be a problem to meet 90% of data capture, knowing that Brussels for example has on average more than 100 rainy days per year (World weather & climate information, 2016). Dropping too much data would mean this constraint would not be met. Therefore, if no hardware improvement (e.g drying chamber) nor data corrections are developed, the low-cost sensors will not meet the DQO. In this the case, the data could be used as defined in the previous scenario.

If the measurements are corrected so the data capture constraint is met, the sensors could then be used and displayed on official Belgian air quality maps. The low-cost sensors could be widely spread across Belgium, which would lead to much more accurate models and assessment of Belgium's air quality. The sensors' deployment should be preceded by a test of their accuracy, using a Standard Operating Procedure is also necessary, as well as a defined maintenance plan. Building and setting up the sensors should be done by public institutions, because if they want to use those sensors for official measurements, they need to be sure it is correctly set up and maintained.

Each monitoring station costs between 5,000 and €30,000 (Castell et al., 2017), while a low-cost air quality sensor costs around €30. The maintenance costs of a monitoring station are also much more expensive than the low-cost sensor's. If the latter meets the DQO, there is thus an opportunity to cut monitoring station costs by replacing some of them with low-cost air quality sensors. Indeed, Joost Wesseling (NDIPHE) explained that replacing monitoring stations with low-cost sensors is one of the Netherlands' goals.

If the VUB's study has shown the sensors to have a positive impact on awareness and behavior changes, workshop could be organized so citizens would be involved. However, the citizen-sensors [1] should be used to improve the models, raise awareness, but should not be directly used as official measurement points, e.g for European reporting.

3.2.2 What benefits for which institutions

Chapter 2 exposed in detail the different organizations working on air quality monitoring, allowing us to understand their internal organization, as well as their vision and

[1] Which mean the sensors are built, set up and maintained by citizens.

relations with each other. As a reminder, figure 3.4 below shows the organizations responsible of air quality monitoring for each region and between them. We have seen that each of them is independent in its operations. Hence, each public institutions can take advantage from the sensors in a different way. In this section, there will not be any distinction between the scenarios mentioned previously. This approach has the purpose to facilitate the analysis and keep the focus on the potential benefits.

Figure 3.4: Organizations working on air quality monitoring in Belgium.

Section 2.1.3, page 41, showed that Flanders has started working on low-cost air quality sensors via the project LIFE VAQUUMS. They aim at testing and working with 4 types of sensors, including the SDS011. This initiative shows that the VMM is aware of the potential of the inexpensive sensors.

Evelyne Elst, who is responsible of this project and answered an interview as part of this thesis, was at a low-cost sensor building workshop organized by Influencair during the month of June.

The VMM could benefit from Influencair's expertise, as people working on this project have been doing so for more than a year now.

- They have acquired a good knowledge of the hardware and the software, as well as its strengths and weaknesses. Such information takes time to gather as there is very few literature about the SDS011 on the internet.

- Influencair also has a large network interested by the topic, which can benefit the VMM if they want to set the sensors up via citizens. Unfortunately, this network is mostly composed of people located in Brussels. However, it also includes people who are actively deploying sensors in Ghent, Antwerp and Leuven. They could also be interesting for the VMM to work with.

In conclusion, the VMM, and more specifically the LIFE VAQUUM project, is an interesting collaborator for Influencair in order to test the accuracy of the SDS011, and, depending on the results of the test, address the opportunities. In addition, collaborating between them would be an incentive for Brussels Environment and the ISSeP to support low-cost sensors deployment in Brussels and Wallonia[1].

In the case of positive results from the accuracy test, Brussels Environment could spread sensors to raise awareness, as the city of Leuven has done it in the last months. The city provided a room for free so Leuvenair could hold two workshops. In addition, the first 100 sensors were funded by the province of Vlaams-Brabant (Maarten Reyniers, Personal communication, June 6, 2018). Such initiative would fit Brussels Environment's vision considering they stated in the "Plan Air-Climat-Energie" that raising awareness was one of their goals. The organization currently suffers from an important pressure from the citizens, notably through movements such as "filter-café-filtré", which blocks roads near schools every Friday to claim a cleaner air, or "Clean Air Bxl" which puts pressure on the government towards less air pollution. Organizing workshops with citizens so they can also understand and measure air quality would be a good way for them to get closer to them and show that they are open to collaboration.

In addition, measuring on a hyper-local level would be beneficial for them to measure traffic pollution (and more generally Brussels' pollution) in more details. Such knowledge could lead to better policies.

[1] Only if the accuracy test gives positive outcome. Cfr. sections 3.1 and 3.2.1.

Again, all those possibilities depend on the accuracy test's results and the scenarios detailed in the previous sections. However, the greatest benefit Brussels Environment could gain from such action would be earning citizens' trust.

In Wallonia, the "Cellule Permanente Environnement Santé" (CPES) also stated their will to raise awareness about air pollution and its impact on health. Wallonia currently has 23 Particulate Matter monitoring stations, which is little for its territory[1]. Therefore, getting more measurement points would be valuable for Wallonia, in particular around Namur, Mons and Tournai (see map, figure 3.5 below). There are currently very few low-cost sensors set up in Wallonia compared to Flanders and Brussels. Spreading the sensors via workshops would be a good opportunity for them to raise awareness and get more data points.

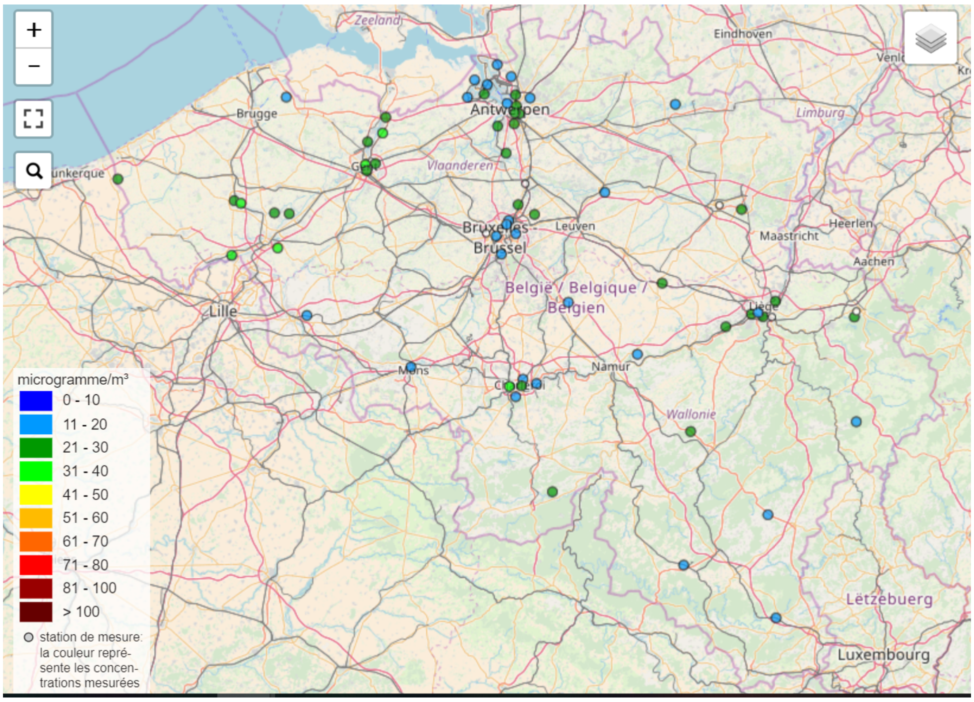

Figure 3.5: Monitoring stations in Belgium. Source: IRCELINE.

Concerning IRCELINE, they are responsible of aggregating the data provided by the three regions, but not to make measurements themselves. As it is a decentralized organization, it seems inconvenient for them to set up sensors. However, as they are responsible

[1]Flanders has 69 for a smaller territory.

of the national models defined in section 1.3.3, page 27, if the sensors appear to be sufficiently accurate, they could deploy low-cost sensors if their aim is solely to improve those. Raising awareness among citizens is however out of their scope, this task should then be let to the other organizations described above.

Conclusion

This thesis has exposed how Belgian public institutions could benefit from low-cost air quality sensors. It has discussed the sensor's accuracy and its potential impact on people's awareness.

Clarification was provided about how the device works as well as the monitoring stations currently used to provide official pollution measurements. The scope of the paper was limited to low-cost sensors and monitoring stations measuring Particulate Matter, a pollutant composed of droplets and solid particles, responsible for 500,000 premature deaths in Europe. The public institutions working on air quality monitoring in Belgium have been presented, with an overview of their activities, responsibilities and objectives. Afterwards, it was possible to detail the methodology to follow in order to test the low-cost sensors' accuracy. The following section addressed the possible uses of the low-cost sensor depending on the accuracy test's results, introduced in the form of scenarios. Finally, an analysis of each institution's potential use of the low-cost sensor was given.

The most valuable opportunities that have been mentioned are, first, the possibility to raise awareness among citizens, and second, getting more measurement sites. Awareness is necessary for people to realize the impact of their life habits on their own health, while getting more measurement locations would enable public authorities to give a more accurate assessment of people's exposure to Particulate Matter pollution.

Three findings stand out in this paper:

- Although there are clues that the measurements done by the low-cost sensors provide a good estimation of pollution concentrations, their accuracy decreases at very high and low humidity levels. Therefore, it is necessary to conduct an accuracy test before public institutions could use them. In addition, laws regulate the way

European states gather air pollution measurements. Indeed, for the measurements to respect the European legislation, they should meet the Data Quality Objective (DQO). To assess if the low-cost sensors meet the latter, a preliminary 6 months data collection phase is necessary. It consists of co-locating low-cost sensors with monitoring stations in 4 areas, distinct in their meteorological conditions and exposure to traffic. The collection phase is to be followed by the analysis of the data. The outcome of this analysis will produce, among others, the level of Expended Relative Uncertainty, which will determine whether the low-cost sensor meets or not the DQO.

- The outcome of this accuracy test will widely define how and if public institutions can benefit from the low-cost sensor. This paper distinguished three possible scenarios: if the low-cost sensor meets the DQO, if it does not with a relatively small difference, and if it does not with a relatively great difference. The scenarios discuss if and where the measurements could be displayed, and whether they would need some sort of correction. The scenarios also explain in which cases the sensors should be owned by the public institutions or by citizens. This mostly depends on where the measurements would be displayed, and if raising awareness about air pollution is one of the public institutions' goals. The scenarios also touched on what should be done for the sensors to be useful in improving the models assessing air quality on a high resolution.

- Finally, the paper discussed how each Belgian institution working on air quality monitoring could use the low-cost sensor, considering their vision, their current stations network, and more. We saw in this section that some of them are already interested by this inexpensive technology, while others deny its reliability.

This thesis did not address public institutions' possible measures to reduce air pollution, nor people's behavior changes[1], even though those matters would be interesting topics for further research. The connection between the sensor's accuracy and people's awareness has not been developed either, even though there is certainly a link between them that deserves to be studied.

In addition, we only discussed one low-cost sensor for one type of pollutant. Other low-cost devices exist for Particulate Matter measurement. Those should also be considered

[1] Those changes could be reducing ones car usage or avoiding wood burning.

and tested, as their performance and reliability could be better than the one mentioned here. Changing focus towards those would be an interesting direction if the low-cost sensor mentioned here performs poorly during the accuracy test. As for the low-cost sensors monitoring other pollutants, plenty of technologies exist. Their potential should also be assessed so opportunities, comparable to the ones developed here, could also be exploited.

"What gets measured gets managed." - Peter Drucker

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Annexes

Interviews

Olav Peeters, Scientific Coordinator at IRCELINE - 31st May 2018

Thomas:

What institutions are your in contact with, and how do you communicate together?

Olav:

We communicate with the AWAC, the "Agence Walonne de l'air et du climat" for Wallonia, the Vlaamse Milieumaatschapij for the Flemish region, and in Brussels that would be IBGE. All those are the three regional agencies behind us. Well there are actually two cooperation agreements, you can check the details on our website. It is more about collecting environmental data under the umbrella of the national focal point which is sort of a central thing within the European wide IO net, a committee of experts, the main experts on several environmental topics but for air quality there is a much closer cooperation between the regional agencies and most notably the SMOG protocol. The communication is streamlined between the competent authorities so actually the decision to go or not on SMOG alert is actually taken by us. We a re not a separate legal entity but everyone working within IRCEL-CELINE is actually dispatched from the regional environment agencies.

The SMOG alert limits the speed limit to 90kh/h on the highways, its based on forecasts. If we forecast an average of more than 70 µg/m^3 for two consecutive days then we are going to that part of the SMOG protocol. There is an information threshold at 50 µg/m^3, it depends on the region what advice is sent. If you look at the website, there is documentation for the details, for example when the Flemish region gave advice not to use wood as a combustion for central heating, there is an alternative during winter period for example.

But yeah, every region has its own interpretation, there are advice in any case but the decision whether or not we will enter the SMOG alert is actually taken by us, it is centrally coordinated. We try to have the same scientific basis across the whole country allowed for regional access if you want.

Thomas:

Are you also in contact with ISSeP ?

Olav:

Not ISSeP, it is only used for the maintenance of the regional network in Wallonia but they are not a partner as such to our cooperation, AWAC is the official partner.

Thomas:

Is it you who communicate to the people or are you only in contact with the regions' institutions who then communicate with the public?

Olav:

Actually in practice is means that the regions tell us what we need to say via which region. There is a slight degree of autonomy in the sense that via the website of the regional agencies they might do some additionnal communication but we send the mails. We have a mailing list for when people register in their language and they get a message in their language. But, for example, the Brussels Region communicates a lot via SMS than the other regions, and there are people dispatched from the IBGE to CELINE. Actually, the SMS sending comes from our offices in the name of Brussels Environment.

Thomas:

Then you are responsible of most of the communication if I understand well?

Olav:

It depends a bit, but in general most of the public communication is actually done by us. We are also the first contact of the media in case of there is any questions. And then we see whether we forward the question to a specific domain expert in the different regions. It depends a bit but in general communication to the public is done by us.

Thomas:

So it there other organizations that you collaborate with, private or public ones?

Olav:

Officially, we get a lot of questions from NGOs: Greenpeace, Friends of Europe, a lot of NGOs. Also, more regional ones like Bond Beter Leefmilieu but also BRAL in Brussels or even Leuvenair or InfluencAir, we try to be as open as possible. But there is of course no official corporation agreement or anything. The only cooperation is between the regional agencies, it is actually what IRCELINE is, there is a permanent cooperation agreement between the regions and then on a European scale we are part of the European Network.

For example we were in contact with the RIVM (Netherlands National Institute for Public Health and the Environment) and the Netherlands, but also Airparif in France, UBA (German Federal Environment Agency) in Germany and also for example the Environment Agency in the Luxembourg where the gas bottles are calibrated. So there is a lot of European cooperation on air quality because air quality is of course something that never stops at the border. 60% of the pollution in Belgium is from foreign sources, but we are still net exporters of air pollution, so there is a lot of transnational exchange of air pollution and the cooperation certainly reflects that.

Thomas:

Thanks to that you can also comply with the European obligations then?

Olav:

Yeah well for example within the agreements of the European framework, it is about the establishment of the European data infrastructure. So all process with data specifications, service specifications, meta data specifications and so forth. We have been in contact with IGM a lot which is a federal institution. So it depends but since everything besides the north has been rationalized concerning the environment, of course there are less relevant contacts to the federal level. "Bureau du Plan" also use our data. On a federal level we are mostly a data provider.

Thomas:

I'm a bit surprised that you tell me there is not much cooperation with the federal because I've read recently that the goal of the federal is to assure a coherent national plan concerning air quality.

Olav:

And yes? And where did you find that?

Thomas:

In the official website of Belgium: "www.belgium.be" and it was also written in a paper from the ULg.

Olav:

Well ok. It is probably because before the cooperation agreement was signed air quality was fully done by a federal agency, the IHE. Many of the people who started working in CELINE were either dutch speaking or french speaking, they used to work for the IHE before they came. And that was the first generation that came to CELINE, they all came from the IHE, they came from the same organization. The last person who came from the IHE is now retired but a second generation now is working here. We still have our own identity here at CELINE in practice but we all got here via the regions. It's not that we have our own independent budget but we try to see what needs to be done then look for the ones at the regions who want to see that is necessary for a good cooperation.

Thomas:

Alright. And do you give advice to the regions on what should be done or do you simply provide the data without working on the solutions?

Olav:

Since we are not above the regions, we are part of the regions, we try of course when we see issues to advice. An interesting case was the fact that the Walloon region now has real traffic stations. It was something which we always said to the Walloon region that they needed traffic stations. In Charleroi, according to the European criteria, they needed traffic stations but, well, the fact that there finally got movement in the whole situation was the fact that Greenpeace started a law case against the Walloon government and now finally there is a bit of movement to get real traffic stations. But actually the other regions are not that much better, there's one true traffic station in Antwerp and *incomprehensible* but in Brussels it's also a little bit off, it used to have one in Belier but it only measured NO_2, not PM for example. There was a technical reason because the station is in a building of the European Parliament and the accessibility is difficult, that's one thing but also the inlets cannot be straight up, which would have an influence on the PM measurements so that was part of the reason why they never installed PM in that station. But in any case, there is also discussion about whether the criteria are really satisfied within the Brussels region as well, and also for the Flemish region one of the traffic stations is actually also pretty limited. If you look at it on a global scale we have about 70 to 80 stations in the three networks and only one true traffic station that's a bit too bad.

Thomas:

Do you often have meetings with the regions to assess the quality of the air?

Olav:

Yeah well we have a coordination meeting on a regular basis, every two to four months. The high level of the representatives from the regional agencies come together and we talk about what needs to be done. But there is no way that we can pressure anyone to do what we see. We can ask them and negotiate, but in the case of the traffic station the external pressure worked much better. And there in a certain way regional agencies also see the added value of citizen science networks like InfluencAir or Leuvenair because it is not that the regional agencies don't want to do something about it, but the problem is much more a political problem.

Politicians are scared to really go for a solution, they are scared of enforcing the policies which are necessary to improve air quality. By reducing traffic volumes, by doing something on the topic of wood burn, because it is still associate with coyness. As soon as we and the regional agencies start talking about the negative impact of wood burn we have politicians, like recently a politician claimed that the government is "littling the population" by telling them what they have to do. They say "the government should let us do what we want to do", and actually the discussion is very similar to what the discussion was all about when 10 or 15 years ago we talked about smoking in public places. People see it as an infringement of their personal freedom but actually it is an infringement of the personal freedom to the people who don't want to breathe that air, which needs to be protected in this case, that's very clear. There's not way to win the argument against doing something against that type of pollution.

Especially the fact that we have a regulation on ventilation, as soon as you start renovating your house you need to think about active ventilation of the rooms as house become better insulated they need to get more ventilation. That means sucking the air from the outside into the living room, the sleeping room of the kids. I did some measurements in my house and you see that the concentration just accumulates and you create an unhealthy environment, the house smells like someone is doing barbecue inside of your house. But so the only solution I found was switching the ventilation system but ventilation systems are nowadays built so you can't switch them off anymore. So it becomes a serious issue during winter time but still politicians see it as win words by saying "we shouldn't do something about it because our liberty would be infringed upon".

Thomas:

So do you mean decision takers are not willing to give advice and make up policies because they are afraid of the potential reaction of the people?

Olav:

Yes, it's about being afraid of the reactions of the people. And the Green party is also going that way. They also see that part of their voters are very attached to, see wood as a green alternative, because it's CO_2 neutral source. But it could be CO_2 neutral if they used their teeth to cut down the trees like a beaver. But ok, of course the CO_2 emissions of cutting a tree down is limited but still you need transport the wood, it depends from where the wood comes from but still the pollution is really not to be underestimated. There is Benzene, high CO emissions which is highly toxic, the air quality is seriously going to deteriorate if you have a wood stove. So there are a lot good reasons to do something about it but the public awareness is maybe lacking, people don't have a good judgment of how much air pollution is actually generated, so we try to come up with good number to make them aware. For example 4kg of wood is actually equivalent to 100km driven by a diesel vehicle. Or a new number which we will publish in November in the yearly report of the Flemish region only, that 133 wood stoves is equivalent to the PM being produced by the ring of Antwerp, which is also pretty impressive. So we are already at the stage where there are more PM emitted by people burning wood than by traffic but of course air quality is a complex method, with different types of pollutants, but for PM, for primary emissions of PM there is more PM being emitted by wood stoves than by traffic. There are emissions of traffic of course but there are also emissions of wood burn. In the industry in the last decade there has been quite a lot of emission reduction, reduction has been overtaken by increases of traffic volumes in general. A lot of the game has been used up by either driving faster of more more kilometers per person.

Thomas:

So in the end, do the regions give advice to the citizens or not at all?

Olav:

The Flemish Environment Industry does send recommendations on wood burn, there is a clean communication on asking people to not use wood as a heating source if there is an alternative available. That's a gentle reminder: "You are actually polluting the air, seriously, could you please at least today not do it?". And only during Christmas. That's a very soft approach, not a legal one, no fine, because it's something difficult to enforce of course. If the government would go for a ban, you need to enforce it somehow. And actually the regulation at the moment is so that the communes are responsible for policy concerning wood combustion, they can decide for themselves what they want to do. It's not the regions that do the advice on those days but at the moment, if you want to know precisely I can check with my colleagues, not 100 percent sure that the advice is done by the Walloon region, does it also refer to wood I will have to check. In the Flemish regions there is at least a clear advice not to use wood.

Thomas:

I saw that you use modelizations to see how air quality evolves in Belgium. Can you explain how they work and what you use it for?

Olav:

We use CHIMERE as a base and then add some things to it. CHIMERE is developed by a Ecole d'ingénieur close to Paris, it's a well known model, you can find it. But then there is RIO-IFDM and RIO-IFDM-OSPM. RIO is a version of 4 by 4 kilometers resolution. The thing with RIO is that we make intelligent estimation based on land use. If you have a measuring point to the east, an industrial area there and to the west you have a forest, you can expect that the concentrations on the east are different than to the west. That is behind the real model. So it is intelligent special interpolation, but underneath is Krigin based but you have a delta value based on land use classes, which makes it much more effective than any Krigin modelling could ever be. Of that there is also a 1 by 1 km gridded version but the improvement of the data is such that it is just interpolating the 4 by 4 grids via other criteria, but it doesn't improve the data that much. It is mostly for visualization purposes that we do that.

Then you have the RIO-IFDM which is actually a coupling of the grid as your back road if you want, and looking within each grid cell where do you have high emissions like highways, industries' point sources using meteo parameters: wind direction and speed. Then an estimation of where the pollution will end up, knowing where is comes from, under certain conditions.

That was IFDM, and then you have RIO-OSPM which is taking street canyons into account. Because in a street canyon the pollution is trapped so you have higher concentration. IFDM is an open street model while the OSPM would be a model that also takes into account the street canyons.

Thomas:
So the OSPM is a 3 dimensions model?

Olav:
Yes, in my personal opinion a 3 dimensional modelling is not necessary in that case, it's more about finding the right relations between yes or no if it's street canyon, because in the end you end up in a 2 dimensional street canyon. So since OSPM is indeed a 3D model, there is a lot of computational burden and we are busy looking for a different way to model it.

Thomas:
And so what is exactly a street canyon?

Olav:
Actually we are looking more into a definition of what a street canyon is, so it is more a question of finding the right ratio between the width of the street canyon and the height. Then you end up with a value below or above 1 which will tell you if it's street canyon or not. You can find definitions of a street canyons online, and some estimates that when you are above 0.5 you have a street canyon. It's a definition questions, but width versus height is certainly a good criteria, also how long a street canyon has to be, if it is only two buildings across of each other it's gonna really create a street canyon effect because of the wind. We need a clear definition so we can automate it in the GIS system.

Thomas:
In those models, do you use the data provided by the monitoring stations or only land use and other variables?

Olav:
They all use the measured data as the input, yes. Also real time meteo. But without the measurements we cannot do any modelling.

Thomas:
Then I was wondering, if it would be interesting for you to have more measurement points to assess or to improve your models. As I saw at the bottom of some maps there is mentioned "The data is not validated and should not be used for any study

whatsoever", perhaps it could then be usable for such purpose. And perhaps the sensors from InfluencAir could be used then, as they currently do it with Curieuzeneuzen.

Olav:

We are aware of the Curieuzeneuzen project, 20 000 sampling tubes sites. That data we are using for validating RIO-IFDM-OSDM. There is indeed a nice case of how we use data from citizen science projects for model validations. But yes, these tubes are well established techniques and the thing not to be underestimated is the fact that the technology in Curieuzeneuzen has been standardized across the whole data set. They asked for the first floor on the window facing the street.

I know that in Leuvenair for example they do collect some meta data with the sampling points and that is a very interesting topic to investigate. With the Leuvenair data we have some data now we can use to indeed have a look at how we can correct the data. I mean, validating the data, we are busy, we will start a long term comparison between the low cost sensors, then we will put up 15 sensors for PM, ozone, and NO_2. We will compare them next to reference material then we will have a much better idea about the accuracy of the sensors after that study.

Then we will also try to come to a document called "Standard Operating Procedure", a check list of how you should install the sensors, some guidelines to respect when you install such a device. Another question we have is how long do the sensors produce reliable results. My personal feeling is about 6 months that you can trust the sensor and after that your pump starts to malfunction, the speed of your air blower is extremely important. And after some time, the pump cannot handle it anymore. It's a classic measuring device problem. So we will need to keep in mind how long a sensor has been used.

And since these sensors are very cheap, actually, putting everything together is more expensive than the hardware itself. We should really see the sensor itself as a maintenance cycle we need to replace often and maybe have some other correction strategies, for example using the model data but also some reference stations, combined with sensors. Sometimes you have pollution situations which are not modeled which clearly have an impact. But if only one sensor picks it up, it's maybe less likely to be a real situation, but also there could be a neighbor that started a barbecue and it stated something real. But those spikes are a bit shorter. That's a very interesting discussion of how can we identify malfunctioning sensors and see how we can replace them.

In any case, in Leuvenair they pick episodes like street cleaning in a certain area of the city. It's very interesting and it's clear that what they are measuring is also the reality.

They certainly pick up barbecues from neighbors and so forth. On the topic of wood burn, in certain areas of the city, I'm pretty confident that the sensors are producing pretty good enough results and we need to look at ways of getting rid of the background if you want. Then we can use it for model data and see what parts a local contributions. That looks for me a very promising purpose of the semi-conductor particulate matter measurements because in general what we see is that for PM we are now at a stage where usable results are being produced. There still remains the issue of very high humidity and very low humidity. But actually, those are relatively easy to correct. Why? Because you do have a humidity measurer on the device itself and it would be possible to have a longer period of time to estimate when the problem starts, at 75% of relative humidity, or is it maybe 80 or 90. Where does the calibration occurs when we compare it to reference material? So actually in real time we could correct this.

Thomas:

But how comes that in Curieuzeneuzen, the sensors only run one month over the whole year? Does it provide enough data?

Olav:

The assumption behind Curieuzeneuzen is that if you measure the month of May, it is very representative of the whole year. That's the assumption. Your sensors could be used for hourly values which produce of course different possibilities of correcting models so we could correct our models in real time. I think that there is certainly a role for those types of sensors but we need to see how. I think we are at the moment it is more an exploratory part of seeing how to correct it so it provides usable results, it has not been done yet. There are several rules to jump through but actually it looks pretty promising yes. And that's also nice to see that there's this willingness from your side and from our side to cooperate on this topic so there should be a possibility. We can in any case not say now that they will be used to validate the models but it's a possibility.

Thomas:

You said you think the sensors can last perhaps 6 months, then are those 6 months enough to represent the whole year concerning PM behavior like one month is sufficient concerning NO_2?

Olav:

With the PM2.5 there is certainly something to be done with the data but what we could for example do is, first of all know how the measurements deteriorate when there is relatively high or low humidity. Then we set some criteria for excluding data, then we work with the data that is left. Then we can use that for validation. Besides the Standard Operating Procedure which is also a very important topic, but also the station representativity. Also, very important topic, do you install your sensors street side or do you do it in the garden? You can see it as a part of the Operating Procedure, both are interesting to know actually. Because sometimes your ventilation is in the front of the house, sometimes in the back. So it certainly tells you something about the local variations of air quality. You might miss the barbecue of your neighbors with a sensor at the front of your house but a sensor on the back will clearly show this type of impact. Now during winter time, they could be busy heating their house with a fire place.

Some people live closer to some big work infrastructure than others. Is it more a urban background situation, a city center, is it a street canyon? It would be interesting to have a list of categories to classify stations. That's where we need to put attention also.

Thomas:

Wouldn't it be a problem to delete some of the data then ? Would it still be usable ?

Olav:

There is a European minima for data capture. Look it up, if you google for minimum data capture you can find the value. There's this thing about 5 percent for maintenance which you can use but make me doubt a little bit. The official is actually 90 percent data capture but you are allowed 5 percent on top of that for maintenance. It should be ok for low cost sensor networks. It's a sensible approach, there are certainly periods that can be lost because of maintenance of because of other parameters like relative humidity. It's something to look at, but we can also say for ourselves that we need at least so much data to make weekly averages.

Thomas:

Now is it possible to be in contact with someone that could explain in detail how a monitoring stations works to understand the technology better?

Olav:

I started in the calibration lab so I know how the measurements work.There should be people near your place that could talk about it with you. I also have the keys of all the

Flemish stations if you want. If you are somewhere in Flanders or close to Brussels maybe we could meet in the calibration lab in Brussels. Let me discuss it with the colleagues.

Thomas:

Can you give me a quick overview of how the monitoring stations work in Belgium?

Olav:

Sure. So let's start with particulate matter because that's what you are into. At the moment in Wallonia, they use a device from Grimm, it's a German producer which measures PM the optical way. It measures the number of particles in different size classes. So many particle which are smaller than 1 micro meter. There are different sizes measured, so different size classes. Then you have an algorithm behind it which converts the number of particles per size class to mass. But of course, you can make very different estimations. A particle of the same size of lead and salt have a totally different mass, I'm sure you're aware of that. So it very much depends on the performance of the algorithm whether you have a good conversion or not. That is the Grimm.

What we also see with the Grimm devices, which measure both PM2.5 and PM10, is that when they get calibrated, the masses of PM2.5 and PM10 get separate from each other as time passes, the two values get close to each other until they are calibrated again. It doesn't give us much confidence but the measurements have been shown to be equivalent to the reference. So in air quality a model frame has reference methods which you need to show equivalence to with the device that you use. It was possible to show equivalence with the Grimm to the reference measurement.

The reference measurement is actually gravimetric, so you have a filter in which air is being sucked, the filter is weight before the measurement starts and after the measurement you can estimate how much mass is actually collected by the filter. That is the reference method. So you have some Grimm in Wallonia and in Brussels but for the rest they use the gravimetric method. The best device out there at the moment which is TEOM FDMS. The TEOM is the measuring device and the FDMS is actually a column above it that does the drying and so forth to prepare the air for the measurement. The measurement itself is actually a thrilling device so if there is a lot of mass, the thrilling device will thrill a little bit less because there is more resistance and it can more hardly go up and down. It is much more related to mass itself, it's not a conversion but it's really about mass. I know that some people have done a long term study of measuring devices from the English network in the UK and in Germany. The networks were side by side over a long period of time, there were two devices next to each other which diverged from 60 percent, it's a lot. Just to say, even the TEOM FDMS can be wrong. Particulate Matter mass is very difficult to measure accurately.

In the Flemish network they replaced all their PM sensors with Fidas ones, from the brand Pallas, it is an optical technology. The Fidas does something similar to the Grimm but much more well developed in my opinion. You also have in the device itself, you can install a filter to do reference measurements. There is a size distribution of particle count per size class, and then a conversion to get from particle number to mass. In your case, I think you should best compare the measurements from the SDS011 to something like the Fidas because the measuring technique is similar, it's both optical. They have similar issues if you want but the Fidas has much more reliable.

Thomas:
And doesn't the Fidas have problem with humidity? How does it deal with it?

Olav:
Is has a dryer in the column itself as far as I know. For the technical details, you should look up in the manual. I'm pretty sure there's a drying mechanism because it's a well known issue. And probably it has a relative humidity sensor that is used for correction. It's a good inspiration to improve the measurements of the smaller semi-contact sensor. The technique is similar but you don't have as many size classes of course. Really small scale classes are measured, the Fidas has a lot of different size classes, I'm not sure how many but it should be around 20 classes while the SDS011 has 2 of them. I also think that the SDS011 has a limit of 1 micro meter, so everything under 1 micro meter is not measured. The Fidas has a much lower detection limit.

Guy Gérard, Responsible of the air quality department at ISSeP - 13th June 2018

Thomas:
Pouvez-vous m'expliquer quelles sont les compétences de l'ISSeP et ce que vous faites exactement?

Guy:

Nous exploitons le réseau de mesures de surveillance de la qualité de l'air en Wallonie pour l'aspect scientifique et l'aspect technique. Tout ce qui est administratif et légal est une compétence de l'AWAC. Ca vous pouvez trouver dans un arrêté du gouvernement Wallon qui définit les rôles de chacun, je peux vous envoyer les références si vous le souhaitez. Je vais vous envoyer tous les documents, il y aura la transposition de directive et d'autres documents.

Thomas:
Pouvez-vous m'expliquer ce que fait l'AWAC ?

Guy:
Ils interviennent plus pour l'aspect permis et l'aspect réglementaire. Ce sont eux qui ont la responsabilité de l'évaluation de la qualité de l'air en Wallonie. Donc par exemple si les valeurs limites ne sont pas respectées, on constate qu'une moyenne n'est pas respectée ou qu'il y a trop de dépassements, c'est l'AWAC qui est chargé de faire un plan de remédiation ou proposer des mesures pour que les concentrations diminuent.

Thomas:
Vous ne donnez donc pas de recommandations ?

Guy:
Non, ce n'est pas à nous de faire des plans. On nous consulte aussi de manière officieuse mais officiellement ce n'est pas à nous de le faire.

Thomas:
A part l'AWAC, y a-t-il d'autres institutions avec lesquelles vous collaborez en matière de qualité de l'air?

Guy:
Il y a le CEPES aussi, qui se focalise sur l'aspect santé. Ils étudient les relations entre l'environnement et la qualité de l'air et la santé. C'est la Cellule Permanente Environnement Santé. Egalement avec CELINE avec qui vous avez été en contact. La raison d'être de CELINE c'est que la plupart des données doivent être rapportées à l'Europe qui ne reconnait pas les régions mais ne reconnait que les états. Donc le point de contact de l'Europe pour les données belges, c'est CELINE. Et CELINE intervient aussi dans un domaine où on n'intervient pas, c'est tout ce qui est prévision. Prévision des épisodes de pollution.

Thomas:

Donc vous ne touchez pas aux modèles que CELINE utilise pour la visualisation de cartes?

Guy:

Pas pour les prévisions, mais pour tout ce qui est interpolation on travaille aussi dans ce domaine, l'AWAC y travaille aussi via la Faculté Polytechnique de Mons. On travaille un peu tous les trois là-dessus.

Thomas:

Utilisez-vous les mêmes modèles ?

Guy:

Non ce ne sont pas les mêmes. Donc les modèles ne donnent pas toujours les mêmes résultats et ce n'est pas toujours évident de dire qui a raison et qui a tort.

Thomas:

Pourquoi n'utilisez-vous pas les même modèles? Y en a-t-il un plus performant que les autres?

Guy:

C'est simplement parce que CELINE a plus développé celui qui était utilisé en Flandres, puis-ce que CELINE regroupe les trois régions, c'est le modèle RIO. Et la région Wallonne a utilisé un modèle qui a été développé par les facultés polytechniques de Mons. Donc c'est un peu historique. Nous, grâce à un projet de recherche qui s'appelle "PM-Lab" on s'est lancé aussi dans l'interpolation. Et comme on est arrivé un peu après dans le domaine on a pris le meilleur des deux.

Thomas:

J'imagine que vos modèles se basent aussi sur les données des stations de mesures.

Guy:

Oui tout à fait.

Thomas:

La région Wallonne vous impose-t-elle des façons de travailler ou êtes-vous totalement indépendant?

Guy:

On est tout à fait indépendants dans la manière de travailler. Donc la stratégie est développée par l'AWAC. Par exemple, pour le moment, on essaye d'implémenter des nouvelles stations en milieu urbain, car c'est vrai que notre réseau souffre un peu d'un manque de stations en milieu urbain ou de stations "traffic", à proximité d'un axe routier important. C'est l'AWAC qui décide, c'est un peu une décision du ministre, ça retombe sur l'AWAC qui est l'autorité compétente qui dit "Il faut installer une station urbaine à Charleroi, une station urbaine à Liège et à Namur", ensuite c'est l'ISSeP qui fait son choix et qui va sur le terrain et qui sélectionne les sites de mesure. Donc nous sommes tout à fait indépendants pour choisir. Ce n'est pas nous qui décidons de la stratégie initiale d'installer une station supplémentaire, mais à partir du moment où c'est décidé on a carte blanche pour l'installer à tel ou tel endroit.

Thomas:
Qu'en est-il de vos stations de mesures de PM10 et PM2.5 ?

Guy:
Il y a 23 stations qui mesurent les PM10 et PM2.5 en région Wallonne. C'est une technologie optique à diffraction laser. La méthode de référence en matière de particules c'est la gravimétrie. Donc ça veut dire que c'est la méthode de référence imposée par la directive. Donc il faut prendre un filtre vierge, le poser dans certaines conditions d'humidité et de température, on peut même faire plusieurs pesées. Vous le mettez sur le terrain, vous prélevez pendant 24h, vous récupérez le filtre, vous refaites la pesée dans les mêmes conditions de température et d'humidité. Vous comprenez que c'est quelque chose qui consomme énormément de temps et qui ne permet pas d'informer la population en temps réel puis-ce que le résultat vient quelques jours voire quelques semaines après. Donc tous les réseaux en Europe utilisent des méthodes automatiques, et il faut démontrer qu'elle est équivalente à la méthode de référence. Donc on a cette méthode de diffraction laser qui est une méthode automatique de monitoring, mais on doit régulièrement la comparer à la méthode de référence pour prouver qu'elle est bien équivalente. Pour les autres polluants on utilise chaque fois la méthode de référence mais ici c'est pas le cas, tout simplement parce que c'est trop lourd en main d'oeuvre et puis ça ne nous permet pas d'informer en temps réel la population sur les concentrations en PM10 et PM2.5.

Thomas:
Avez-vous aussi des relations relatives aux mesures avec l'Europe?

Guy:

Au point de vue mesures, oui car on participe à des exercices inter laboratoires où plusieurs réseaux Européens se retrouvent. Ca se fait souvent en Allemagne ou en Italie et chacun vient avec son matériel, on compare nos résultats, donc ce sont des exercices d'inter comparaisons entre laboratoires.

Thomas:

Devez-vous faire des rapports pour démontrer que la méthode de mesure est équivalente?

Guy:

Pour ça, oui on doit faire un rapport.

Thomas:

Disposez-vous aussi d'un laboratoire d'analyse?

Guy:

Pour ça on a une chambre de pesée, donc c'est une chambre frigorifique avec des conditions de température et d'humidité qui doivent être réglées, qui sont assez sévères. Et c'est là qu'on fait les pesées des filtres.

Thomas:

Comment est-ce que vous faites pour démontrer que la méthode optique est équivalente à la méthode gravimétrique ?

Guy:

On met à côté d'une station automatique un préleveur sur filtre, et on pèse ce filtre avant et après et on fait des séries de plusieurs dizaines de comparaisons. Il y a toute une procédure, un calcul d'incertitude qui doit être réalisé et on montre qu'on est bien en dessous d'un certain niveau d'incertitude. Donc c'est une comparaison méthode de référence - méthode équivalente.

Thomas:

Vous rendez donc un rapport à l'AWAC, est-ce tous les mois, tous les trimestres ou autre?

Guy:

Pour les PM10 et PM2.5, les données sont transmises en temps réel via le système informatique à CELINE et à l'AWAC. Sinon le rapport est annuel sur l'évaluation de la qualité de l'air. Les valeurs limites des directives sont souvent des évaluations qui doivent se faire sur une année complète. Sauf pour l'Ozone pour laquelle il y a parfois des mesures à prendre quand il y a des pics de pollution mais pour les autres polluants ce sont des évaluations sur une année civile.

Thomas:
Est-ce possible de voir un de ces rapports annuels ou est-ce confidentiel?

Guy:
Oui bien sûr je peux vous en envoyer un.

Evelyne Elst, Project Coordinator at VMM - 25th June 2018

Thomas:
Can you quickly present yourself and what you do at the VMM?

Evelyne:
I'm Evelyne Elst, since January 2018 I'm working at the Flanders Environment Agency (Unit Air) as the project coordinator of the LIFE VAQUUMS project. In this project we will test 18 different low-cost air quality sensors (PM, NO2 and O3). For more information about the project, find the flyer in attachment or visit our website www.vaquums.eu.

The Flanders Environment Agency (abbreviated VMM) is an agency of the Flemish government working towards a better environment in Flanders. The VMM is active on three domains: water, air and the environment.

More information on what the VMM does can be found on:
https://en.vmm.be/about-vmm and
https://en.vmm.be/publications/vmm-an-introduction.

Thomas:
What does the VMM do exactly? What are your roles concerning air quality in Flanders and more generally in Belgium?

Evelyne:
Concerning air quality, VMM is responsible for the official reference measurements in Flanders. In addition, we make an inventory of the emissions. We are only authorized

to work in the Flemish region. IRCELINE gathers the information of the three Belgian regions and reports to the European Commission. Note that VMM is not responsible for the policy making on air quality, nor are we inspecting businesses.

Thomas:
The IBGE has made the "Plan Régional air-climat-énergie", do you also write such plan? Do you write other kind of reports ? If yes, can you explain them briefly?

Evelyne:
Since this plan is related to policy, it is not the responsibility of VMM. We do write one substantial yearly report on the status of the environment in Flanders (Flanders Environment Report (see also next question): https://www.vlaanderen.be/nl/publicaties/detail/mira-flanders-environment-report-system-balance-2017). In addition, a lot of smaller reports are available (https://www.vmm.be/lucht/publicaties-lucht). And VMM/IRCELINE does the official reporting towards the European Commission

Thomas:
Can you describe the different departments of the VMM concerning air quality and what each of them do?

Evelyne:
All groups working on air quality are gathered in the 'Air monitoring, environmental reporting and communication department'. Within this department there are groups specifically working on air quality.

- Air unit: responsible for the reference measurements in Flanders and for reporting of the results. We also measure pollutants which are not included in the European Air Directive (for example black carbon, ultrafine dust, dioxins and PCBs, a wide range of PAH and VOC, we do the chemical characterization of fine dust on several locations,...). In addition, we also give advice what impact large (new) constructions have on air quality.
- Team emission inventory air: responsible for making the inventory of the emissions in the air and for the reporting of the results.
- MIRA (Environmental reporting unit): responsible for making the Flanders Environment Report (MIRA = Milieurapport Vlaanderen). This report describes, analyses and evaluates the status of the environment in Flanders. It also discusses the environmental policy and gives views on possible environmental developments.

Thomas:

What organisations does the VMM work with concerning air quality? IRCELINE, ISSeP, IBGE ? Other organisations in Flanders responsible of energy, mobility or health ? How do you collaborate?

Evelyne:

At IRCELINE some employees of VMM are working together with employees from Brussels and Wallonia. VMM is working together very closely with IRCELINE. We also cooperate with Agentschap Zorg en Gezondheid (https://www.zorg-en-gezondheid.be/). Some projects are co-financed by VMM and Agentschap Zorg en Gezondheid. In addition, we work together in the steering groups of different projects financed by other agencies. Some of them try to find the link between air pollution and health (https://www.lne.be/milieu-en-gezondheid). They also perform human biomonitoring campaigns. Other try to implement the impact on air pollution in spatial plans. (https://omgevingvlaanderen.be/)

There are also many international projects in which VMM cooperates with other European environmental agencies and companies. A short overview of these projects can be found on: https://en.vmm.be/projects. But note that not all project descriptions are (yet) available in English. More can be found in Dutch on: https://www.vmm.be/lucht/projecten. The project I am working on is LIFE VAQUUMS. It is a European project during which we will test 18 different low-cost air quality sensors (fine dust, nitrogen dioxide, ozone) both in the lab and at a reference station (www.vaquums.eu).

Thomas:

How does the deployment of new monitoring stations take place ? Who decides what, and how?

Evelyne:

It is based on the European legislations which describes where should be measured, how should be measured and on how many places measurements need to be taken. In addition, we sometime also place extra measurement stations, for example near certain companies. Therefore, we often work together with the Flemish Environmental department's environmental inspection unit (https://www.lne.be/afdeling-milieu-inspectie), with companies and with local governments.

Thomas:

Do you collaborate with municipalities in some ways ? If yes, how, and can you give an example ?

Evelyne:

Yes sometimes we have collaborations with local governments. For example, on the request of the local governments we measure the air quality on additional places in Antwerp (more specific fine dust, black carbon and nitrogen dioxide) and in Ghent (nitrogen dioxide). In addition, we often cooperate with the local governments of the municipalities where we have a reference station (e.g. to find a suitable location).

We also advise local governments on how to start up measurement campaigns, for example with passive samples (which were also used in Curieuze Neuzen).

Thomas:

Do you communicate with citizens in some way ? Giving them advice to avoid/reduce air pollution perhaps ? Or else ?

Evelyne:

We have an extensive amount of information on our website (far more in Dutch than in English), which is written in a way that it is accessible for citizens. It also includes some tips and tricks (https://www.vmm.be/tips) and some very nice infographics (on the bottom right of https://www.vmm.be/lucht).

Which can also be interesting for you, is that we are currently involved in the Interreg project Zuivere Lucht (https://www.vmm.be/lucht/projecten/zulu), during which a toolbox for citizen science will be developed (normally available by the end of this year). Also in the LIFE VAQUUMS project, we will develop some webtools citizens can use to visualize (maps, graphs, . . .) and analyze their sensor data.

Furthermore, we answer a lot of information questions (like yours) asked by citizens. We also provide heating advise (not to burn wood for heating) on days with fine dust peaks. Finally, we also give smog alerts on days with high fine dust concentrations, which results in lowering the speed limits (90 km/h). More information on the latter can be found here: http://www.verkeerscentrum.be/verkeersinfo/dossiers/fijn-stof.

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