VAQUUMS

Guidelines on applying (low-cost) air quality sensors

1 Introduction (1p)

In recent years an increasing number of air quality measurement methods became available, but the reliability of their results is often unknown. Within the LIFE VAQUUMS-project (Various Assessments of air QUality Measurement methods and their policy Support) we investigated which (mobile) sensors can be a valuable additions to the reference measurements. The project aimed to assess the reliability of air quality sensors (particle matter, nitrogen dioxide and ozone). After a literature review and an expert consultation, the most promising sensors (see sensor selection procedure) were tested both in the lab and in the field. Based on the results of the LIFE VAQUUMS-project, we will develop guidelines and protocols for the correct use of air quality sensors. In this way, everybody will be able to measure the air quality in their neighborhood.

This document reflects the aforementioned guidelines. Our consortium learned a lot while running the VAQUUMS-project:

- The experiments themselves obviously provided information on sensor performance, but also on getting a great number of sensors operational, running them a year long etc.
- Questionnaires in the early stages of the project provided insight on the motivation for using sensors, types of sensors used and the aim of sensor networks (use cases)
- Workshops with both experts and municipalities (>10) provided insight in the link between sensor performance and applicability on the one hand and the context of local deployments on the other

In this document we gather guidelines on how to apply (low cost) air quality sensors. The information is based on the above experiences. The usability of this document was our primary focus. It does not provide a detailed account of the lessons learned, workshops etc. but rather presents the most sensible way forward, according to our consortium.

2 Using the VAQUUMS guidelines

We distinguish two elements in our guidelines: a draft air quality sensor charter and a set of key recommendations in support of this charter. It has to be noted at this point that we present a draft charter only. It is based merely on our experience during the VAQUUMS-project and should be elaborated at the regional, national or European level.

The concept of the charter is based on the open data and citizen science data charters developed in Flanders. Both charters entail a set of principles supporting open data developments at the local level or optimal data handling in citizen science projects. In analogy the VAQUUMS Air Quality Sensor Charter presents principles supporting the local deployment of air quality sensors by cities and municipalities.

As for the charters that inspired us, this charter should be further developed in co-creation with the relevant stakeholders. Regarding air quality sensors at least cities, research institutes, environmental agencies and sensor developers should be consulted.

However, during the VAQUUMS-project we also learned that a set of principles is not sufficient for many municipalities. Therefore we also provide a set of key recommendations aimed at regional to European actors. These recommendations focus on supporting the charter with relevant frameworks, up to date information etc.

2.1 Practical

The charter and recommendations provide a list of principles with brief descriptions of each principle or recommendation. In a second part of this document each element is elaborated slightly by providing information on why it was included based on the VAQUUMS-experience and links to examples, relevant documents etc.

Ultimately, cities and municipalities could opt to sign the charter indicating they intend to adhere to its principles when implementing air quality sensor networks. Given that enough cities in a region sign the charter, this provides a solid basis for cooperation, common way of working and clear expectations for technology providers, environmental agencies etc.

The principles are ordered according to the stages of implementation, i.e. plannings stage to data interpretation. Hence municipalities can start working with the initial principles, gain experience and take on the next principles when they are ready to proceed.

3 VAQUUMS Air Quality Sensor Charter

This charter is presented as a first draft only, based on experience gained and lessons learned during the VAQUUMS-project.

The below principles are intended as actionable steps that can be taken into account at the local level.

3.1 First set of principles – preparing an air quality sensor network

#1 Formulate your goal(s) early on

What is the purpose of the air quality sensor network you are considering? Formulate a hypothesis, research question or the envisaged outcome you would like to see achieved by the sensor network. This enables specificity and maintaining focus when you further define your sensor network. Your goal should be as concrete and specific as possible, try to use the S.M.A.R.T. principle in its definition.

#2 Maximise the specificity of your use case

Building on the outcome of principle #1, try to be as specific as possible in defining (a) use case(s) for the sensor network. Define your primary stakeholders, who should/will benefit from the sensor network? What problem(s) will it solve, what needs will be addressed? When will the sensor network be considered as successful?

#3 Cooperate with regional experts

Actively seek out advice from regional experts and involve them well in advance. These can be institutes routinely monitoring air quality, cities or municipalities who have attempted a deployment themselves etc. Remember you can also learn from past failures here. Ultimately expertise should be sought on: available sensors and their performance, deployments (logistics, maintenance) and interpretation.

#4 Consider using sensors in conventional setups

Build experience – through cooperation – by adding air quality sensors to conventional monitoring setups. High quality results are ensured while a post-hoc analysis will provide insights in what could be achieved using just air quality sensors in the near future.

3.2 Second set of principles – acquiring air quality sensors

#5 Tailor your approach

There is no "one solution fits all" when it comes to air quality sensor networks. Your deployment should be tailored to the outcomes of principles #1 and #2. Additionally the local context, perhaps even meteorology – depending on the use case – will influence your approach. Use a specific calibration (as opposed to a regional or broad calibration), tune your data aggregation …

#6 Include intercomparison in public tender

It is preferrable to include an intercomparison of the air quality sensors on offer in any public tender. Use a specific testing protocol during a prolonged period, preferably up to 3 months if achievable, at a reference monitoring site for the intercomparison. Alternatively, recent intercomparisons results at a neutral reference site – in comparable conditions (meteorology, sources) – should be provided by the participants.

#7 Develop the sensor network through experimentation

Demonstrate the applicability of a sensor network step-by-step. Using the specificity introduced through principle #2 and the tailoring in principle #5, zoom in on a specific use case to start. Build the use case from there by adding deployments that serve the demonstration of other use cases and scale up gradually.

3.3 Third set of principles – using air quality sensors

#8 Monitor relative humidity and temperature concurrently and reliably

Many – if not all – air quality sensor readings are influenced by ambient (relative) humidity and temperature. Invest in a good quality, concurrent monitoring (or other data source) of these parameters to greatly improve calibration results.

#9 Monitor cross sensitivities

Gas sensors in particular are prone to cross-sensitivities with other gases. The cross sensitivities mainly depend on whether oxidizing or reducing chemicals are monitored. It is essential to monitor these chemicals influencing the sensors at hand in order to achieve decent performance.

#10 Set up a well thought out QA/QC procedure

Air quality sensor networks produce a large amount of data. Apart from the data architecture point of view, this should also be considered from a quality perspective. Set up a QA/QC procedure that minimizes manual interventions while still identifying the most unreliable data points.

#11 Focus on complementarity to other data sources

In support of principle #10, linking to reference or other high quality datasets will allow following up on calibrations, drift etc. Linking to modeled datasets (and vice versa) will add full domain coverage (and granularity). Also linking to cross-domain datasets will benefit quality control and analysis or interpretation (e.g. mobility, crowds, meteorology, industrial activities …).

#12 Encourage further sensor development

Adhere to the open data principles and in particular share intercomparison results whenever possible. Continuously deploying an air quality sensor at a reference site and providing the dataset as open data can provide opportunities for advances in calibrations etc. Reach out to maker communities, data scientists etc. and challenge them to improve sensor results (e.g. through hackathons). Finally, also share both successful and unsuccessful stories of sensor deployments.

4 Key recommendations

4.1 Set up a standardised testing protocol

An EU-wide protocol for comparative studies between air quality sensors and reference instruments would be highly beneficial. It allows a more direct comparison of the available studies, increases overall efficiency as studies do not have to be repeated and increases stability for technology providers as benchmarking is transparent.

Relevant link: [LIFE VAQUUMS test protocol]

4.2 Maintain a database of sensor/reference intercomparisons

The benefits of a standardise testing protocol are maximised when test results can be found more readily. Existing databases such as the Airmontech database can provide a solid starting point. Ideally a common and easy to understand visualisation of the test results can facilitate the use of this database. Ample visualisations currently exist. The LIFE VAQUUMS consortium has developed its own easy-to-use visualisation but does not recommend one over the other. This merits debate upon implementation of the database and is also linked to the parameters in the standardised protocol.

Relevant link: [Airmontech DB]

4.3 Support local air quality sensor initiatives

As per principle #3 local actors will seek advice on aspects such as sensor performance, deployment and interpretation. Providing a single point of contact or clear guidance on who the relevant experts withing a region are, facilitates the application of this principle. An standardised approach to starting up local initiatives – such as the LIFE VAQUUMS roadmap – can save time and cost on both ends.

Relevant link: [LIFE VAQUUMS roadmap]

4.4 Encourage further sensor development

Apart from principle #12 of the charter above, sensor development can also be encouraged with low effort initiatives. Opening up some reference monitoring locations allowing sensor developers to co-locate sensors easily can stimulate developments. At the same time the reference institute can gain experience in sensor performance and guide developers in relevant improvements to sensor performance.

4.5 Relevant Open Data sources

Make sure relevant open data sources are readily accessible (e.g. through APIs) and well known in support of principle #11.

4.6 QA/QC tools

Similar to the standardised testing protocols a standard QA/QC protocol – and perhaps tools – can be developed. This would improve cities and municipalities' capacity in managing performance of air quality sensor networks. Within LIFE VAQUUMS a simple QA/QC procedure was used, tailored to low cost sensor devices.

Relevant link: [LIFE VAQUUMS technical manual]

5 Supporting information on charter

#1	Formulate your goal(s) early on
Description	What is the purpose of the air quality sensor network you are considering? Formulate a hypothesis, research question or the envisaged outcome you would like to see achieved by the sensor network. This enables specificity and maintaining focus when you further define your sensor network. Your goal should be as concrete and specific as possible, try to use the S.M.A.R.T. principle in its definition.
Relevant information	Websites with guidance on designing experiments: ▪ www.hoemeetiklucht.eu ▪ www.samenmetenaanluchtkwaliteit.nl

#2	Maximise the specificity of your use case
Description	Building on the outcome of principle #1, try to be as specific as possible in defining (a) use case(s) for the sensor network. Define your primary stakeholders, who should/will benefit from the sensor network? What problem(s) will it solve, what needs will be addressed? When will the sensor network be considered as successful? *Roadmap "assessing needs", empathy sessions, stakeholder mapping, design thinking*
LIFE VAQUUMS findings	Working with innovation experts, we learned it is better to accurately address a single need and build from there, than addressing 10 needs from the start without satisfying them completely.
Relevant information	▪ LIFE VAQUUMS roadmap "assessing needs" ▪ Design thinking ▪ Empathy sessions ▪ Stakeholder mapping

#3	Cooperate with regional experts
Description	Actively seek out advice from regional experts and involve them well in advance. These can be institutes routinely monitoring air quality, cities or municipalities who have attempted a deployment themselves etc. Remember you can also learn from past failures here. Ultimately expertise should be sought on: available sensors and their performance, deployments (logistics, maintenance) and interpretation.
LIFE VAQUUMS findings	It is advantageous to involve experts early on as even the best performing sensor can not compensate for poor (experimental) design or other overlooked aspects of air quality monitoring. E.g. a longer "before" measurement increases your chance of assessing policy impact irrespective of the monitoring device.

Relevant information	▪ Many institutes provide routine sensor intercomparisons o LIFE VAQUUMS test results o Airmontech database on air pollution monitoring technologies (EU) o AQ-SPEC (US) o INERIS and LNE (FR)

#4	Consider using sensors in conventional setups
Description	Build experience – through cooperation – by adding air quality sensors to conventional monitoring setups. High quality results are ensured while a post-hoc analysis will provide insights in what could be achieved using just air quality sensors in the near future.
LIFE VAQUUMS findings	It is currently very difficult to find best practices for sensor deployments, we therefore recommend this principle to start gaining experience and build success stories. Whether you have a successful or unsuccessful story, share it! (principle #12)
Relevant information	Websites providing information ongoing projects, sensor etc. ▪ www.hoemeetiklucht.eu ▪ www.samenmetenaanluchtkwaliteit.nl

#5	Tailor your approach
Description	There is no "one solution fits all" when it comes to air quality sensor networks. Your deployment should be tailored to the outcomes of principles #1 and #2. Additionally the local context, perhaps even meteorology – depending on the use case – will influence your approach. Use a specific calibration (as opposed to a regional or broad calibration), tune your data aggregation ...
LIFE VAQUUMS findings	We found that it is useful to define "minimum viable products" (MVP). These are the cheapest, smallest possible sensor deployments that would still validate a use case and provide useful data on the local level. The MVPs also facilitate a discontinuous, needs based deployment later on.
Relevant information	▪ LIFE VAQUUMS roadmap on sensor deployments ▪ Minimum Viable Product tool

#6	Include intercomparison in public tender
Description	It is preferrable to include an intercomparison of the air quality sensors on offer in any public tender. Use a specific testing protocol during a prolonged period, preferably up to 3 months if achievable, at a reference monitoring site for the intercomparison. Alternatively, recent intercomparisons results at a neutral reference site – in comparable conditions (meteorology, sources) – should be provided by the participants.
LIFE VAQUUMS findings	Intercomparisons – especially in a commercial context – or often very short and encompass just 2 weeks to 1 month. This duration is too short to detect any drift in the sensor signal and the comparison is only valid for the environmental conditions observed. There is also a risk of cherry-picking observations. Hence we recommend intercomparisons in the relevant local context (sources etc.) and during a prolonged period to increase the variation in environmental conditions and potentially detect drift. The local context is important as our tests have shown that e.g. PM-sensors do not detect every type of PM it likely depends on composition as well as size fraction.
Relevant information	▪ LIFE VAQUUMS test protocol

#7	Develop the sensor network through experimentation
Description	Demonstrate the applicability of a sensor network step-by-step. Using the specificity introduced through principle #2 and the tailoring in principle #5, zoom in on a specific use case to start. Build the use case from there by adding deployments that serve the demonstration of other use cases and scale up gradually.
LIFE VAQUUMS findings	This links to the MVPs in principle #5. Think of experiments that would prove an MVP's success and use those to gradually roll out and build your network.
Relevant information	▪ LIFE VAQUUMS roadmap on sensor deployments ▪ Exploration map (explore potential experiments)

#8	Monitor relative humidity and temperature concurrently and reliably
Description	Many – if not all – air quality sensor readings are influenced by ambient (relative) humidity and temperature. Invest in a good quality, concurrent monitoring (or other data source) of these parameters to greatly improve calibration results.
LIFE VAQUUMS findings	It is possible to improve sensor performance through calibrations based on ambient temperature (T) and humidity (RH). However many low cost sensor setups (e.g. in citizen science) suffer from poor quality T and RH sensors, undermining the performance of calibrations.
Relevant information	▪

#9	Monitor cross sensitivities
Description	Gas sensors in particular are prone to cross-sensitivities with other gases. The cross sensitivities mainly depend on whether oxidizing or reducing chemicals are monitored. It is essential to monitor these chemicals influencing the sensors at hand in order to achieve decent performance.
LIFE VAQUUMS findings	Lab performance is always significantly better than field performance. Ambient air composition is very complex and contains many chemicals potentially interfering with sensor signals. This mixture is also continuously changing, which is why lab performance is usually better.
Relevant information	▪

#10	Set up a well thought out QA/QC procedure
Description	Air quality sensor networks produce a large amount of data. Apart from the data architecture point of view, this should also be considered from a quality perspective. Set up a QA/QC procedure that minimizes manual interventions while still identifying the most unreliable data points.
LIFE VAQUUMS findings	Our test results show that a basic validation is required for several sensor types. Typical issues were a.o. spikes in data signals, periods of elevated measurements, loss of signal etc.
Relevant information	▪ LIFE VAQUUMS technical manual (QA/QC) ▪ LIFE VAQUUMS test results

#11	Focus on complementarity to other data sources
Description	In support of principle #10, linking to reference or other high quality datasets will allow following up on calibrations, drift etc. Linking to modelled datasets (and vice versa) will add full domain coverage (and granularity). Also linking to cross-domain datasets will benefit quality control and analysis or interpretation (e.g. mobility, crowds, meteorology, industrial activities …).
LIFE VAQUUMS findings	
Relevant information	▪

#12	Encourage further sensor development
Description	Adhere to the open data principles and in particular share intercomparison results whenever possible. Continuously deploying an air quality sensor at a reference site and providing the dataset as open data can provide opportunities for advances in calibrations etc. Reach out to maker communities, data scientists etc. and challenge them to improve sensor results (e.g. through hackathons). Finally, also share both successful and unsuccessful stories of sensor deployments.
LIFE VAQUUMS findings	During the LIFE VAQUUMS project the Flanders Environment Agency (VMM) designated a number of reference sites as ‘Open Innovation Monitoring sites’. At these locations we provide basic power supply and mounting options for sensor developers. A standard contract is used including recommendations on the length of testing periods. Participating developers hold a kick-off and evaluation meeting with VMM-experts to discuss results etc. This facilitates technological advances in a low-cost win-win for both parties.
Relevant information	▪ Airmontech database on air pollution monitoring technologies

6 Version History

Version	Description
1.0	Version presented at closing webinar