Air quality monitoring using stationary versus mobile sensing units: a case study from Lorraine, France

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Abstract: Air pollution monitoring and impact assessment represents a major objective especially for large and industrial cities, driven by the need to improve citizen liveability. In order to address this challenge and avoid increasing monitoring costs, attention is now being redirected towards using low-cost sensing units and an opportunistic citizen sensing. This paper proposes a comparative study of using various air quality monitoring devices such as: high-reliable fixed air pollution stations, fixed smaller passive tubes and smart mobile sensors, tested through field measurements and citizen sensing in an eco-neighbourhood from Lorraine, France. The air quality evaluation is done through two experimenting protocols. The first protocol involves the installation of passive tubes for monitoring the NO_2 concentration levels inside the eco-neighbourhood, placed in strategic locations highly affected by traffic circulation. The second experimentation protocol aimed at monitoring the NO_2 levels registered at the human level by citizens travelling daily inside the neighbourhood and carrying with them the smart pollution sensor. The findings revealed that the mobile sensors carried at the human level (approximatively at 1.5 meters altitude) detected higher NO_2 concentrations which would sometimes be between three to five times higher than the passive-static monitoring tubes (placed at 3 meters altitude).

1. Introduction

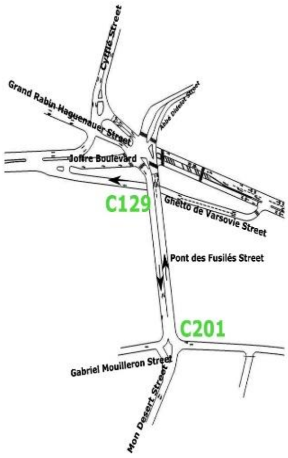
Addressing air pollution problems in growing urban cities has become a major problem due to ever increasing traffic in dense populated urban areas, extended industrialisation and higher energy consumption, insufficient resources for monitoring and various issues in defining adapted policies [1] [2]. The challenge of managing air pollution becomes more difficult due to its dangerous effects on public health and the multitude of air pollution triggering factors. The overall high levels of urban air pollution has been shown to have a significant impact on the health of city dwellers [3]. A recent study published by [4] has shown the significant impact that air pollution has on a local, regional and global scale, placing it among the top ten dangers to human health and well-being. However, there is a lack of quantifying the effects of long-time exposure to air pollutants and its direct impact on health, especially during peak hours in congested city areas.

In an effort to address these issues, the concept of *eco-neighbourhood* has emerged as a response to the above challenges, and became the place of technical, innovative, economic and social experimentation. At the beginning of the 1960s, the first ecological areas ``had a rather small and remote location from metropolitan centres" [5]. Later in the 1990s, the eco-neighbourhoods focused upon demonstrating different urban development settings which were a part of a sustainable development initiative [6]. Today, their role has become increasingly complex because they must meet several principles of sustainable development [7]: 1) involve all the city actors, 2) contribute to improving the daily life by developing a healthy and safe living environment for all residents, 3) participate in the economical and local dynamics, 4) promote a responsible resource management and adaptation to the climate change. The eco-neighbourhoods offer the opportunity to experience and anticipate the evolution of cities by guiding the decision makers. The latest changes in the development of digital tools and design practices (collaborative approach, usage integration directly from the design phase, citizen involvement in experimental smart city projects), offer new perspectives for quantifying the impact of urban changes [8].

Motivation: With the urban project Nancy Grand Cœur (NGC) the Grand Nancy Metropolis in France, wants to rehabilitate the 15-hectares area around the historical train station including its railway and industrial brown field [9]. A visual representation of the train station hosting almost 9 million passengers each year is provided in Fig. 1a). This ecological urban project is intended to be delivered by 2025, and the objectives for this central area are manifold: new fluid mobility, better traffic regulation, reconciliation between historical and modern neighbourhoods of the city, improved air quality, extended green spaces, reduced energy consumption, comfortable homes and offices. An important step to respond to this wide variety of problems is to analyse the air quality inside the neighbourhood, especially at a human level, when passing through the most circulated intersections of the NGC neighbourhood: C129 and C201 (see selected area in subplots b) and c) from Fig. 1). Understanding how high circulated streets impact the citizens on their daily journey-to-work trips is a true challenge which can give a clear insight on how the eco-neighbourhood needs to be reconfigured in order to protect its inhabitants from high air and noise pollution levels.

a) Urban project for NGC by 2020, source: Arep Ville – J.M. Duthilleul.

b) Urban area in 2013.



c) Focus on most circulated intersections.

Fig. 1. *Case study of the eco-neighbourhood "Nancy Grand Cœur".*

Solution: The work presented in this paper is a continuation of our previous studies [10] [11] in which we proposed an integrated air pollution and traffic simulation model for building a simplified NO_2 estimation model which helped predicting and visualizing various environmental changes inside the NGC eco-neighbourhood. Our previous study has used reliable data sets provided by the Air Quality Monitoring Station (AQM) from the local air-quality management centre, mixed with meteorological data. While these data sets are of high accuracy, they only represent global concentrations computed by the AQM station installed at high elevation from the ground (more than 4 meters) in a single location in the city. The real and direct impact that pollution can have at the human level could be completely different than higher dispersed pollution concentrations. We are currently interested in analysing more granular and real-time air quality information, provided by citizens travelling daily in NGC. We believe that providing health risk information caused by air pollution is an important step for raising citizen awareness and triggering changes in their daily travelling behaviour.

The paper is organized as follows. In Section 2 we provide insights on the challenges faced by air quality monitoring, by looking at the international context of air quality evaluation methods. We debate the need of using low-cost mobile pollution sensing units as well as the evolution towards opportunistic citizen sensing which motivates this study. Section 3 presents the case study of NGC eco-neighbourhood and the air quality evaluation methods currently deployed in the city. In Section 3we present the stationary and mobile smart sensing units which have been chosen to conduct the current study, followed by a description in Section 3.2 of the air quality measuring experiments which we deployed in the most circulated intersections of NGC. The results are provided in Section 4 and concentrate around nitrogen dioxide and noise level evaluations, followed by conclusions and future perspectives of the current work.

2. Challenges in air quality monitoring

2.1. International Context

Currently, in many countries around the globe, air pollution is monitored at a regional level by networks of static and sparse stationary AQM stations, equipped with instruments for measuring various pollutants such as: carbon monoxide (CO), nitrogen oxides (NO_x), sulphur dioxide (SO_2), ozone (O_3) and particulate matter (PM). The risk information is often provided as a concentration of pollutants or as an index of air quality (AQI) at a scale which can be easily interpreted by the public. These AQIs can vary in their approach for determining pollutant concentrations, as they follow different regional policies [12] which can differ from one country to another. For example, Canada has adopted an Air Quality Health Index on an 11-point scale obtained from a non-linear combination of particulate matter 2.5 microns ($PM_{2.5}$), nitrogen dioxide (NO_2) and ozone (O_3) [13]. On the other hand, in Europe all countries are required to comply with EU directives such as the Council Directive 96/62/EC on ambient air quality assessment and management, commonly referred as the Air Quality Framework Directive. Therefore the hourly and daily AQIs are calculated on a scale from 0 to 100 by taking into consideration PM_{10}, NO_2, O_3, and where accessible, $PM_{2.5}$, SO_2 and CO [14]. The EU directives recommend as well to install a specific number of monitoring stations for individual pollutant monitoring, based on the number of inhabitants and the geographic partitioning of that area/city (EU Air Quality Directive 2008/50/EC). Although they offer high-precision results, the AQM stations are often high-priced and need a significant amount of resources to be routinely maintained and calibrated [15]. Often, the temporal and spatial resolution of a network of fixed AQM stations is far too sparse to incorporate the contribution of different sources of pollution without significant constraints and assumptions. The AQM stations would offer a global insight over large urban areas but they cannot identify pollution hotspots inside the city centre or around large industrial areas for example. Often, there are no real-time pollutant concentration maps available at high-resolution (<1m) for large urban areas because they require a large amount of data, computing facilities and input details which are not available for many cities [16].

2.2. The need for low-cost sensing units

Recent improvement of low-cost sensor technology has led to the development of a multitude of robust micro-sensing units (MSUs) with a lower power consumption which can be used for detailed air quality surveillance. These MSUs can be used either as individual nodes or in an interconnected distributed network, and would collect high-resolution spatial and temporal data when being mounted on cars, bicycles or carried daily by pedestrians. One of the main advantages of using low-cost sensing units is that they provide more input conditions, especially if they are used in significant numbers for detecting pollution hotspots. Their real-time information would allow a rapid assessment of the pollution problem and would lead to more efficient prevention strategies.

Due to a higher granularity provided, easy to handle functionalities and rapid access to real-time pollution concentrations, various research programmes have started to test both fixed and mobile monitoring sensors [17]. As well, including citizens in the testing and exploration of urban air pollution opens new opportunities for direct environmental awareness, debate and future prevention strategies. Some examples of such projects are: Air Quality Egg [18], Citizen Sense [19] and the Smart Citizen Kit [20], which offer a centralized collection of data, processing and real-time map visualisation, through on-line platforms and mobile applications. These “citizen sensing” projects intend to expand citizen engagement in environmental issues, and help them making changes in their daily journey-to-work trips in order to avoid polluted urban areas. Currently there are various low-cost air quality sensors which are commercially available [21] or prototype sensor networks [22]. For a detailed state of the art regarding low-cost pollution sensors the user can refer to the works of [16].

While this radical change in the air monitoring mentality promises a flexible pollution surveillance solution, the question around the accuracy of the generated data quality still remains. The main downfall of low-cost sensors remains their relatively low accuracy compared to official fixed AQM stations or other benchmark devices [23]. For example, [24] has observed a sensor-specific temporal variation of the calibration parameters, and proposed a periodical calibration of wireless sensors based on the nearby AQM stations which would capture the fine and dynamic spatial variability of pollutants at a high temporal resolution. Questions related to the battery power of the sensors and the life-expectancy of low-cost sensors can also be seen as a drawback for adopting MSUs, but their flexibility and remote-control possibility for data transmission and collection increased their popularity. Together with meteorological sensors for measuring humidity, temperature, wind speed and direction, they can form the basis for assessing pollution levels and produce behavioural changes at a larger scale amongst citizens.

2.3. Towards opportunistic citizen sensing

The idea of using low-cost sensing for monitoring air quality has led to a shift in the air quality data collection, generating the notion of opportunistic citizen sensing, which implies that data collected for one specific purpose can be used for other purposes as well [25]. Involving citizens in the data collection gave birth to the notion of anthropocentric opportunistic sensing, in which large volumes of sensing data are collected, stored and fused for further analysis and interpretation [26]. Using data analytics for extracting meaningful insights from daily air pollution and noise exposure will provide unparalleled feedback to the citizens regarding their daily trips and route choice behaviour. By following the opportunistic aspect, the air pollution analytics can be coupled together with clinical research studies for analysing correlations between citizen movement and biological exposure [27]. Emergency alerts could then be triggered when unusual air quality levels are signalised in specific areas of the city or when a significant number of citizens present clinical side-effects of air pollution exposure.

Our current work is driven by the idea of having a granular insight on the air quality in the city provided by citizen sensing which can provide a supplementary insight for the integrated traffic and air pollution simulation model of NGC. In the next section we present the challenges and experimenting protocols deployed for the current study, which represent an initial step for analysing the use of smart mobile pollution sensors at a large scale in urban areas.

3. Case study

As represented in Fig. 1c) from Section 1, our attention concentrates on measuring the air-quality in two of the most circulated intersections in NGC (C129 and C201) by using collaborative citizen sensing. The NGC project has the initiative to change the structural configuration of these intersections in order to allow a higher inflow of vehicles to cross the neighbourhood every day. A large amount of vehicles in densely populated areas will contribute to an increasing deterioration of the air quality due to higher motor vehicle emissions. In 2012, the U.S. Environmental Protection Agency (US EPA) has shown that 61% of the total emissions of carbon monoxide (CO) and 35% of total emissions of nitrogen oxide were produced by highway vehicles [28]. The complexity of the air pollution lies in its extent and the large amount of factors changing its behaviour, making it even more difficult to implement measures for protecting the citizens. According to the 2012 air quality assessment [29], air pollution is caused by various industrial, commercial, domestic, agricultural activities, but the traffic congestion is the major cause as indicates that 56% of the nitrogen dioxide in the air is caused by road transportation.

Therefore, the objectives of our study are manifold: 1) measuring air quality at a granular level in the city by using smart pollution sensors, 2) prepare the field for integrating citizens in a daily and global air quality data collection and monitoring, 3) provide insights by comparing outputs of stationary and mobile smart pollution sensors and draw guidelines on which source to be considered as reliable.

3.1. Choice of sensing units

In France, the State entrusts the monitoring of air quality to twenty approved AASQA associations (1901 Act) led by the ATMO Federation [30]. Air Lorraine [31] is one of the selected air monitoring associations which is responsible for continuously monitoring the air quality inside NGC and which has been our main reference source for testing the accuracy of the mobile sensor units deployed for this study. As we are currently interested in analysing more granular air quality information, a series of mobile sensing units have been considered. For this paper, we only present the results obtained when investigating two major units which will be detailed in the following. Other comparative studies of smart pollution units are currently under testing and evaluation. The choices have been selected after a thorough analysis of existent sensing units on the market, their accuracy, the feasibility of being used on a daily basis, their costs and daily maintenance. For a state of the art of low-cost mobile sensing units, the user can refer to the work of [16].

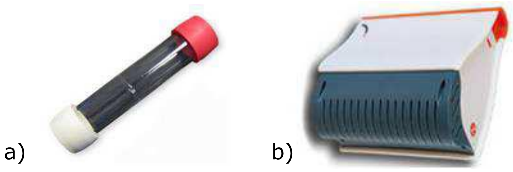


Fig. 2. *a) Passive NO_2 tubes b) Azimut station*

In the following we give a brief discussion about the small air pollution monitoring units which have been chosen for our experimenting protocols, the reason, scope as well as the advantages and disadvantages to use them in the current study.

1. **Passive tubes** (Fig. 2a): they use the technique of passive sampling which is based on the passive transfer of pollutants by simple molecular diffusion of ambient air to an adsorbent specific to the targeted pollutant. The sampling module is in the form of a porous tube, called "passive tube" which is filled with adsorbent. The passive tube are fixed in a protection box attached to a support near congested traffic areas. After the exposure time has elapsed, the tubes are sent to the Air Lorraine laboratory for analysis. The concentrations of pollutants obtained by this technique are concentrations averaged over the entire sampling period. This technique has been used for sampling of nitrogen dioxide (NO_2) and has the main advantage of being low cost (analysis costs under 10 Euros per tube) and not requiring electrical recharge. The passive tubes have been successfully deployed in various project such as the [32] project for characterizing ambient levels of formaldehyde around industrial sites, or for modelling air quality in the eco-neighbourhood Danube from Strasbourg [33], which was highly impacted by intense circulated areas. The main disadvantage of using the passive tubes is related to the fact that the results are analysed at the end of the experimentation period and cannot detect peaks of localized pollution concentrations during congested traffic hours. These tubes have been used for the implementation of the first experimenting protocol, which is detailed in Section 3.2.1. Nevertheless, they represent an accurate base for comparing NO_2 concentrations with official reported pollution levels from the AQM station during our testing period. Due to their long term proven accuracy in various project of the official air quality monitoring organisation, their result can be considered as accurate and highly reliable. They have been therefore used to have a static and accurate representation of the air pollution level in terms of NO_2 monitored inside NGC.
2. **Azimut Station** (Fig. 2b): is a product of Azimut Monitoring [34] which uses electrochemical gas sensors for measuring the NO_2 emissions. Through a portable emission analyser it can provide continuous real-time monitoring of NO_2, O_3, noise, temperature and humidity. The station can be mounted on cars, bicycles and can be carried by hand while its data is transmitted through GPRS, having a 48-hour autonomy. Despite its considerably higher price than passive tubes (average price varies around 200 Euros), the main advantages of this mobile sensing unit relies in its easy installation and utilisation, a two-day autonomy and real-time data visualisation. The station has been successfully used for building the open data portal MyGreenServices by INRIA [35] which offers real-time visualisation of environmental data collected by citizens, generates alert services and has a forum for sharing ideas and best practices in terms of eco-responsible behaviour. In an attempt to promote citizen awareness and trigger changes in the daily travelling behaviour of citizens, INRIA has provided for us an Azimut station for testing, evaluation and comparison. The data analytics provided through the platform have been used for carrying out the second experimenting protocol, detailed in Sections 3.2.2.

3.2. Experimenting protocols

In this section we only describe two of the experimenting protocols we have deployed during two weeks from 29th of April 2015 to 13th of May 2015. The length of the experiments has been tied to project constraints for council approval, unit installation, data measuring and processing. For each experimenting protocol we provide insights regarding the purpose, the materials which have been used, the constraints, as well as the data acquisition for interpretation.

3.2.1. First experimenting protocol:

The first experimenting protocol aims at determining a reliable data source for further comparison of NO_2 concentrations, and validate the findings with the regional AQM station which is placed in the centre of NGC near one of the major transit corridor (see Fig. 3b). For this study, 10 passive tubes provided by Air Lorraine have been installed at 3 meters altitude on street pillars in two intersections of NGC (C129 and C201), by using protection cases and fixing clamps.

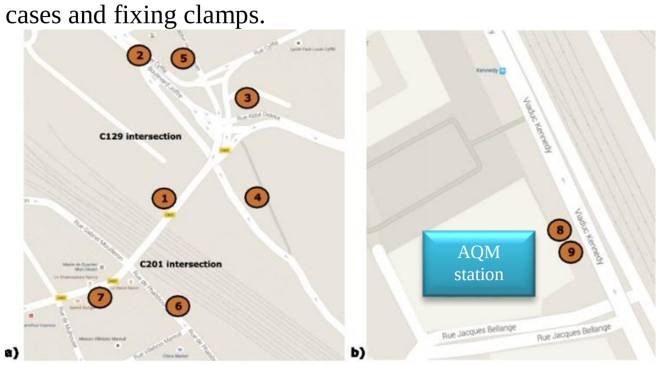


Fig. 3. *Locations of passive NO_2 tubes in NGC placed in a) congested intersections b) near regional AQM station.*

The placement of the tubes has been chosen to be near some of the most congested streets, as represented in Fig. 3. While seven tubes have been used to actively monitor the most congested streets (Fig. 3a), two tubes have been placed near the location of the location AQM station (Fig. 3b), and 1 tube has been kept as a duplicate reference for the others. While the tubes have been previously used successfully in other eco-neighbourhoods [33] and provided accurate results, the placement of the two tubes near the AQM station has the role of double testing and verifying their results during the current experiment. In order for the measures to be accurate and non-saturated, certain constraints had to be addressed; therefore, the tubes were: a) placed far from stopping areas such as traffic stops or parking slots in order to avoid over-saturation of the pollutant concentration, b) located far away from blooming trees or high-ventilation areas c) located at 2-3 meters high and far away from covering structures which would block air circulation. At the end of the experimentation period, the tubes have been analysed by Air Lorraine and the results are presented in Section 4.1 of this article.

3.2.2. Second experimenting protocol:

The second experimenting protocol uses the Azimut mobile station which is carried in hand at a human level during the two weeks experimenting period by volunteers which walk inside the NGC neighbourhood during peak hours. While the tubes have been installed at 3-meters altitude where the pollutant concentrations are starting to disperse in the air, having a direct evaluation of the "perceived" air pollution at a human level represents a major challenge and objective of this experimenting protocol. The daily trajectory of the citizens would pass near each of the 9 passive tube locations presented in the previous section, where the subject would wait for 5 minutes near each tube. The daily circuit is represented in Fig. 4 a) and b). For easing the experimental result interpretation, in this paper we concentrate on collecting and processing data during the evening peak hour from 6pm to 7pm.

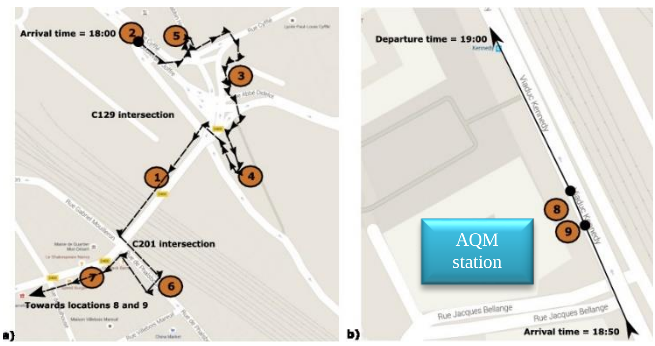


Fig. 4. Daily trajectory using Azimut Station in NGC.

The advantage of using the Azimut station relies in its high flexibility, mobility and real-time transmission of results through the MyGreenServices platform and represented in Fig. 5. The platform offers centralised results, personalised filtering, instant evaluation of concentrations compared to European air quality monitoring indexes, as well as predefined alerts for raising real-time awareness. Having immediate access to results provided a higher awareness regarding the exposure to pollutants for both specialists and citizens travelling in the neighbourhood on a daily basis. Using the station on this predefined trajectory allowed a consistent check of data transmission and quality, which could be then compared and matched to the stationary units from the previous experimenting protocol. Despite the above advantages, the main limitations for applying this experimenting protocol were: a) the daily recharge of the Azimut station in order to prevent a discontinuity in the data collection and b) the lack of multiple Azimut stations which would have been tested in parallel on the same trajectory. Comparison with other mobile sensing units have been further carried, but for the purpose of this paper, we only restrict the analysis to the above protocols. The data profiling and results obtained during this protocol are further discussed in Section 4.2.

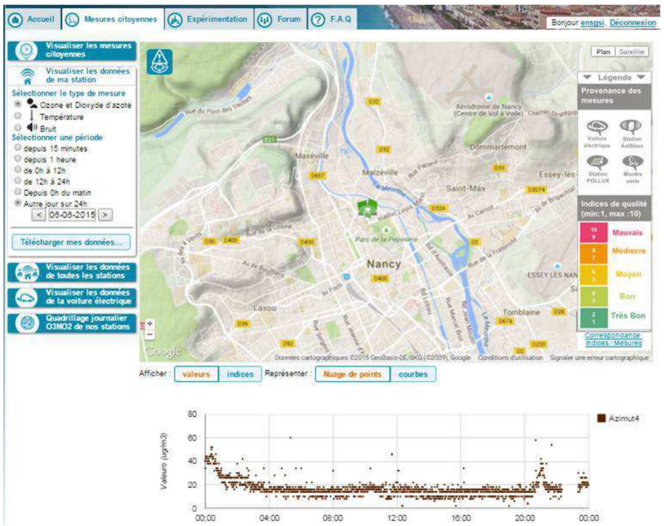


***Fig. 5**. MyGreenServices platform for visualising data collected by the Azimut station.*

4. Data profiling and results

4.1. First protocol results

As previously mentioned in Section 3.2.1 the purpose of the first experimentation protocol was to establish an accurate and reliable source of information regarding the air pollution inside the eco-neighbourhood around main circulated areas (hotspots). The NO_2 levels collected from the passive tubes have been investigated in the air quality laboratory of Air Lorraine *[31]* and evaluated according to the ATMO indexes defined nationally by the French government: see decree of 22 July 2004 related to air quality indices *[36]*.

Table 1 ATMO French National Index scale for NO_2.

Value $[\mu g/m^3]$	Index	Qualifier
0-29	1	Very good
30-54	2	Very good
55-84	3	Good
85-109	4	Good
110-134	5	Medium
135-164	6	Medium
165-199	7	Poor
200-274	8	Poor
275-399	9	Bad
$\geq$400	10	Very Bad

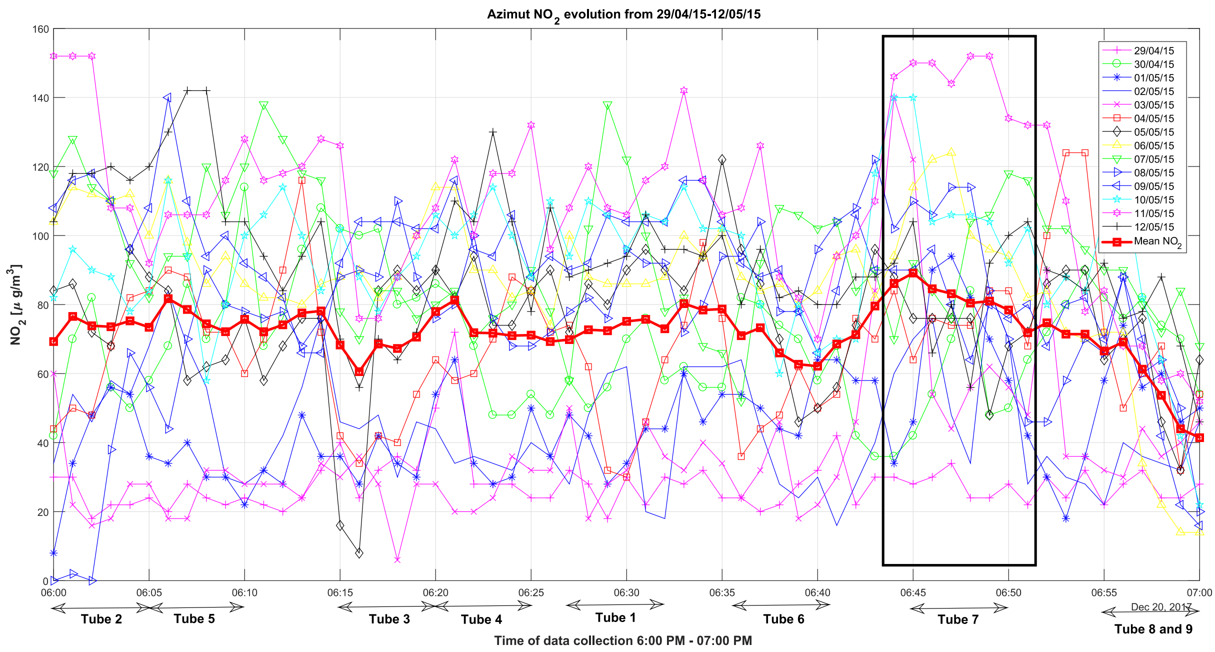


Fig. 6. *Daily NO_2 concentrations registered by Azimut mobile station.*

The evaluation scale is provided in Table 1 and uses indexes from 0 to 10 for different NO_2 concentration levels depending on their severity (0 and 10 standing for a very good, respectively very bad air quality index). The results for each tube are provided in Table 3 and are coloured accordingly to these standard indexes. We make the observation that Tube 10 has been kept as a duplicate for verification purposes, whereupon the low scored value. The results have been obtained during a time period which registered a mean temperature of 13.6°C and a mean pressure of 1013.0hPA. The investigation results indicate that overall the tubes have registered very good levels of NO_2 of index 1 or 2 (according to Table 1). Tube 7 presented higher NO_2 level which is explained by its position near a narrow but highly circulated road in the neighbourhood.

Table 2 NO_2 results of the passive tubes investigation.

Tube Number	Registered Value $[\mu g/m^3]$	Qualifier
1	22.2	Very good
2	27	Very good
3	24.7	Very good
4	14.9	Very good
5	30.2	Very good
6	22.2	Very good
7	53.6	Very good
8	23.2	Very good
9	23.1	Very good
10	0.3	Very good

According to Table 2 tubes 8 and 9, which have been placed near the AQM fixed station of Air Lorraine (Fig. 3b), presented average NO_2 levels ranging around of 23.1-23.2$[\mu g/m^3]$. The official NO_2 concentration registered by the AQM station during the same period of time indicated a level of 24.11$[\mu g/m^3]$ which translates in almost 3.9% error between the tubes and the station. The location of these tubes near the AQM station has been intentionally chosen for re-verifying the accuracy of the passive tubes against the official reported NO_2 levels at the whole urban regional level. The findings confirm the high accuracy of the tubes which have been later used as a benchmark for comparison analysis with the smart mobile stations.

4.2. Second protocol results

The second experimentation protocol aimed at investigating the air pollution and noise levels as reported by the smart mobile unit Azimut. As previously detailed in Section 3.2.2, the experiments took place between the same time-period when the fixed passive tubes have been tested. Fig. 6 presents the NO_2 concentration levels registered for every day of the study period during the evening traffic peak, with the average values ranging from a minimum of 41.48μg/m^3 around 7pm up to a maximum of 91.3μg/m^3 around 6:45pm. Fig. 6 contains as well markers on the X-axis of the time period that corresponds to the waiting time near each tube location along the trajectory shown in Fig. 4 (for example between 6:00pm and 6:05pm the citizens would be stopping near Tube 2 in order to record the concentration in this hotspot of the neighbourhood). But the overall NO_2 concentrations can have different patterns of daily and especially hourly evolution. Our previous investigations in the NGC eco-neighbourhood using a combination of air quality monitoring results and traffic simulation outputs [10] have showed that NO_2 concentrations are highly influenced by the number of cars caught in traffic jams in urban intersections, but also by other meteorological factors such as humidity and wind which play the most important role in the pollutant dissipation or accumulation over the city.

According to Fig. 6, the lowest pollution scores have been obtained during Sunday 03/05/15 as traffic activity in the city centre was low. The highest NO_2 levels reached

152µg/m^3 during Monday 11/05/15 which corresponds to a "medium" towards "poor"' pollution level according to Table 1. This can be explained by an increased traffic demand on Mondays due to citizens returning to work after a long weekend (8/05/15 was a public holiday).
An important observation is that the average NO_2 peak has been registered between 6:45pm and 6:50pm, which corresponds to the waiting time near Tube 7. A possible explanation comes from the narrow street configuration and dense traffic that circulates in this area compared to the other location which have a wider exposure to air flow and multiple circulation lanes. Once again the finding confirms that pollution levels near Tube 7 (which have been registered using the mobile pollution sensor Azimut) are higher than those of the other tube locations. Overall, the mobile station seems to register lower NO_2 concentration levels towards 7pm, at the location of Tubes 8 and 9, which are placed near the AQM station of Air Lorraine. The findings confirm a similar trend between the NO_2 values registered around the tube locations by both stationary and mobile sensors with differences which will be discussed in the following.

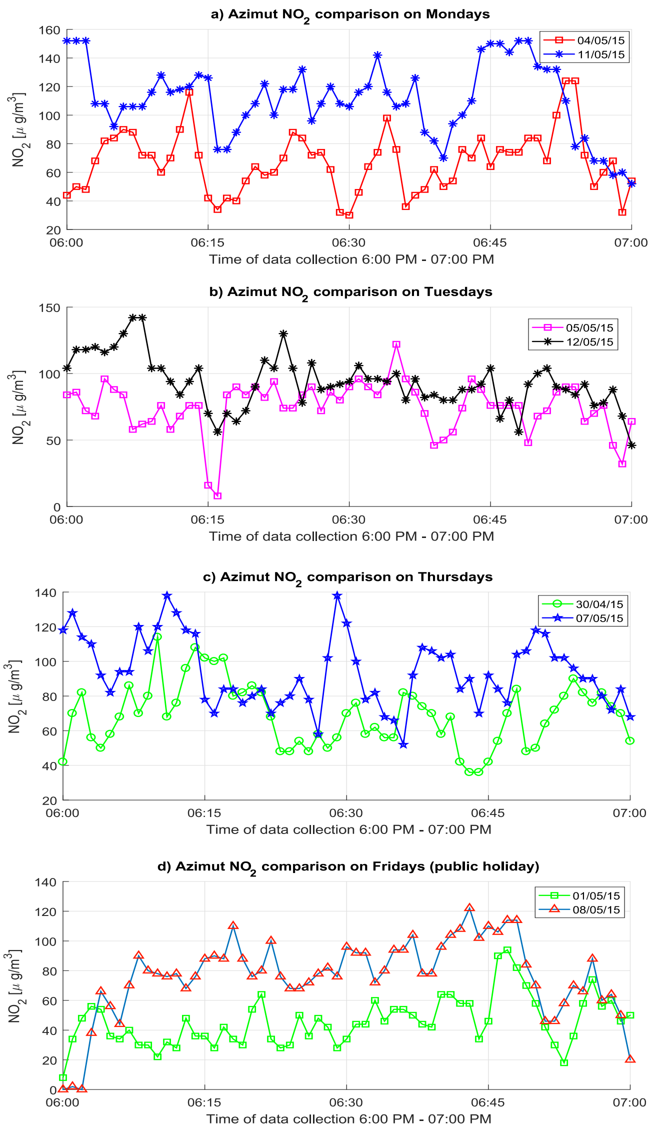


***Fig. 7.** Daily comparison of NO_2 concentrations.*

An important aspect that we considered for evaluating and interpreting this protocol is the weather impact on the NO_2 evolution. Our previously studies indicated that temperature, wind and humidity play a very important role in influencing the pollution dispersion or accumulation in the city and that predicting air pollution levels is not only impacted by specific day profile (day of the week/weekend/public holiday) or mobility patterns (peak/non-peak hours), but also by various exogenous factors which can highly affect the pollutant's evolution in time. In order to understand and interpret the current emission levels, one needs to analyse not only the daily traffic patterns, but also previous weather conditions that have led to the current pollution levels. In the following we conduct a comparative analysis of different day profiles, weather conditions and traffic counts registered during the study period in order to understand how these factors can influence air pollution monitoring at both human level and stationary monitoring stations placed at higher heights.

Fig. 7 presents the NO_2 evolution for Mondays, Tuesdays, Thursdays and Fridays, while Table 3 summarises the Temperature [°C], Humidity [%], Precipitations [mm/h] and Wind [km/h] registered during the study period.

Table 3 Weather conditions during the study period.

Day	T [°C]		H [%]		Pr [mm/h]		W[km/h]	
	6PM	7PM	6PM	7PM	6PM	7PM	6P M	7PM
29/04/15	9	8	80	82	0.70	0.68	10	9
30/04/15	10	9.8	85	86	0.80	0.60	11	9
01/05/15	9.8	8.5	90	92	0.80	0.80	13	13
02/05/15	13	12.8	89	90	0.20	0.20	7	9
03/05/15	18.6	17.6	81	88	0.05	3.50	11	9
04/05/15	22.1	21.2	62	67	0.10	0.06	11	7
05/05/15	20.5	20	46	46	0.15	0.11	20	24
06/05/15	17.1	16.1	40	44	0.05	0.03	24	22
07/05/15	17.4	16.9	41	43	0.10	0.05	9	7
08/05/15	20	18.4	46	60	0.03	0.03	15	17
09/05/15	19.9	19	43	46	0.04	0.03	19	19
10/05/15	21.6	20.9	49	51	0.05	0.01	7	11
11/05/15	25.8	25.1	43	48	0.02	0.01	13	11
12/05/15	24.6	21.8	60	63	0.01	0.05	26	24

The NO_2 concentrations for two typical Mondays are shown in Fig. 7a) and although both days presented an average of almost 550 cars per hour passing the predefined route shown in Fig. 4, one can easily observe that the NO_2 level on 4/05/2015 was significantly lower than that of 11/05/2015. Although the weather parameters during these two days are almost similar according to Table 3 (temperature was around 22-25°C and wind around 11-13km/h), by analysing the three previous days to each chosen dates, one can notice different weather conditions: prior to 4/05/2015 the humidity was higher, temperature lower and there was less sunshine, while prior to 11/05/2015 there were lower precipitations, a higher temperature and more sunshine. This aspect indicates that high humidity, low temperature and high precipitations can reduce the NO_2 accumulation in the city. The finding is also supported by the comparison between Thursdays as presented in Fig. 7c); similarly, the highest NO_2 levels were registered during 07/05/2015, a day with higher temperature,

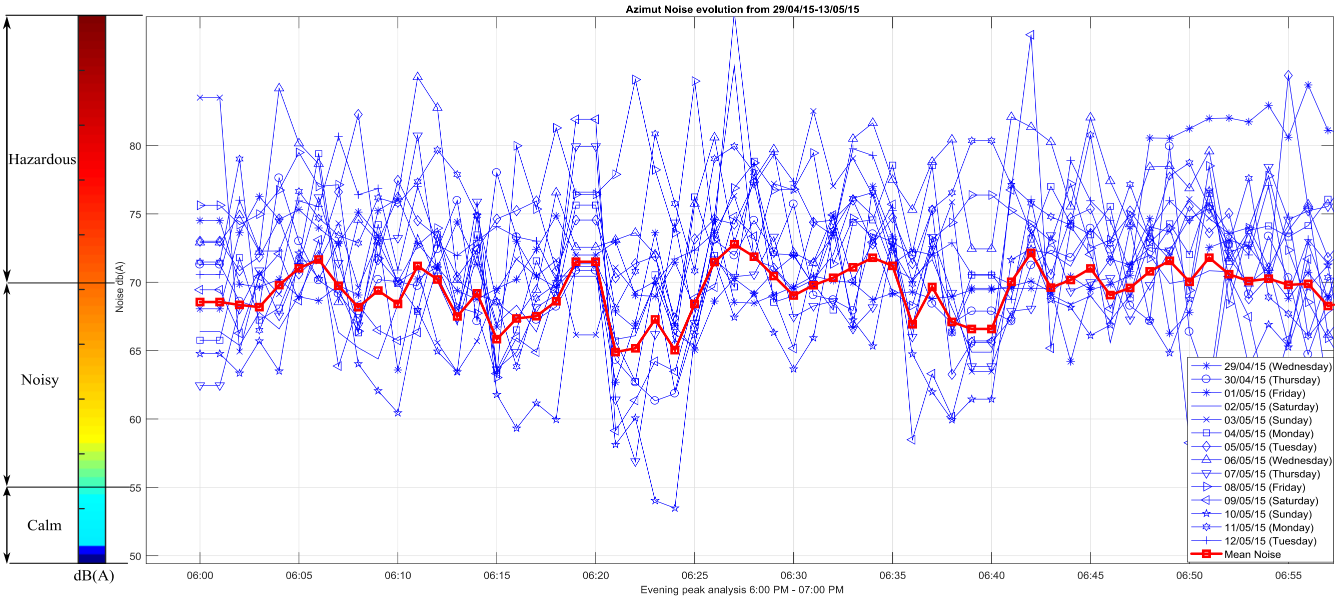


Fig. 8. *Daily and mean noise levels registered by the Azimut mobile station.*

lower humidity and low wind levels, when compared to 30/04/2015 which registered much lower temperatures and higher precipitations.

A special case is the comparison between Tuesdays (see Fig. 7b) when humidity and wind conditions were almost similar during the two analysed days; this translated in similar NO_2 levels, except from 6:00pm until 6:18pm on 12/05/2015 when the higher temperature (24.6$°C$) registered at 6:00pm induced higher NO_2 levels. After the temperature decreased to 21$°C$ around 6:18pm, the NO_2 level presented similar evolutionary patterns as one week before. The comparison for Fridays is shown in Fig. 7d) and strengthens even more our previous findings, with the observation that the lower concentration levels registered on 01/05/2015 were also influenced by the reduced traffic flow as this day was a national public holiday.

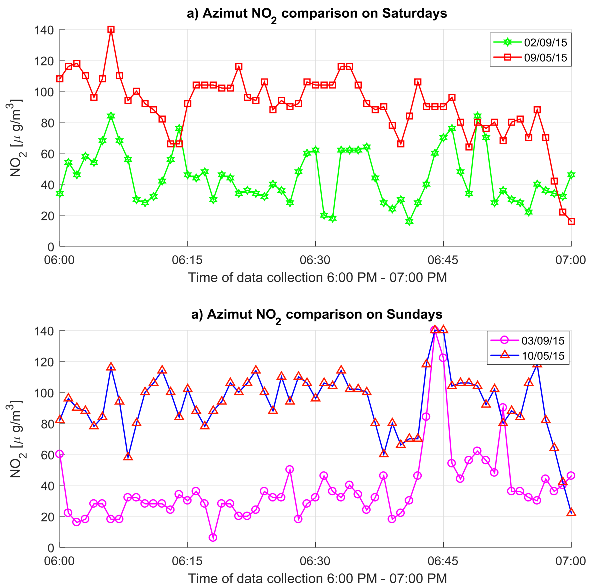


Fig. 9. *Weekend comparison of NO_2 concentrations.*

The public holiday on Friday 1/05/2015 had influenced as well the NO_2 levels on the next Saturday 2/05/2015 and Sunday 3/05/2015, as represented in Fig. 9. The mean number of cars during the evening peak hour averaged around 234 cars, which is almost half than during a normal week day. Moreover, Fig. 9a) and b) indicate a clear difference between the average NO_2 concentrations registered in a weekend preceded by public holiday [44.68$\mu g/m^3$ for Saturday 2/05/2015 and 38.09$\mu g/m^3$ for Sunday 3/05/2015] and the next regular weekend with no public holiday (90.49 $\mu g/m^3$ for Saturday 9/05/2015 and 93.47 $\mu g/m^3$ for Sunday 10/05/2015]. The difference is not only caused by the increased number of cars during a regular weekend, but also by higher temperatures and lower air humidity.

Besides NO_2 levels, the Azimut station has continuously registered noise levels at the human level while following the proposed daily circuit. Fig. 8 presents the mean and daily noise evolution registered during the study period with the associated European noise scale. The measurements indicate that noise levels ranged between 53.48 dB(A) and 89.76 dB(A), with an average reaching often 72.77 dB(A) which indicates a highly noisy/hazardous environment. In comparison to the NO_2 levels which have a dispersed behaviour and are harder to be analysed in time, noise levels seem to have a homogeneous evolution and follow almost similar trends from one day to another.

By undertaking a daily noise comparison similarly to the previous NO_2 analysis, one can easily identify almost similar evolutionary patterns of noise levels during a normal week day (as seen in Fig. 10a and b); lower noise levels were registered during public holidays, when traffic is heavily reduced in the city centre (see Fig. 10c). Overall, the current analysis revealed unexpected high noise levels inside the eco-neighbourhood NGC, which is the contrary objective of the

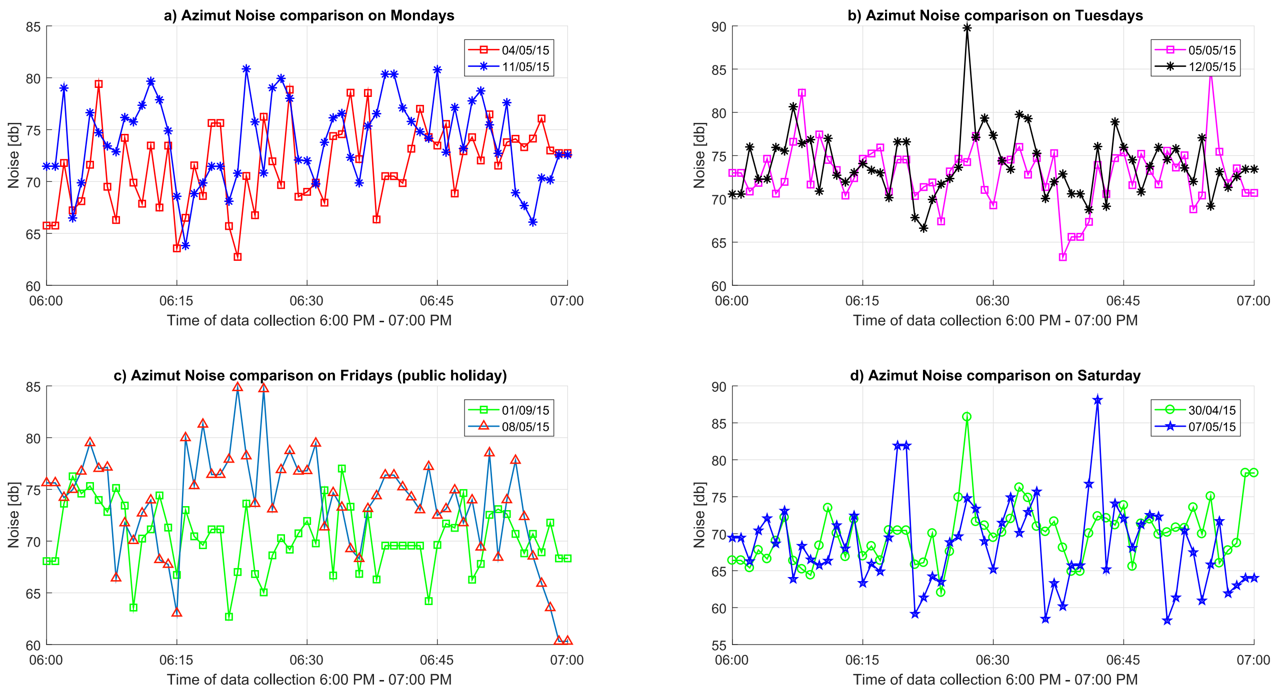


Fig. 10. *Daily comparison of noise levels registered by the Azimut station.*

Grand Nancy Metropolis who wants to increase the liveability for its citizens, not only by offering good public transport services and multi-modal interconnection, but also good levels of air quality, reduced traffic jams and implicitly, reduced noise levels.

4.3. Discussion of results

While the main purpose for this study was to investigate the reliability of available fixed and smart-mobile pollution units, the most important finding is mostly related to the difference between concentrations registered at the human level when compared to those reported by stationary monitoring units. Fig. 11 shows the summary of mean NO_2 levels registered during the whole study period by both the Azimut station and the passive tubes. Although the overall average concentration levels are in good evaluation scales (less than 90 $\mu g/m^3$, the difference between the two experimentation protocols reveal significant differences between these two different monitoring techniques and the different impact that they can have on the citizen daily life. From Fig. 11 one can identify that most of the pollution levels registered by the mobile station carried at the human level near the locations of the passive tubes are almost three times higher than the stationary levels monitored at higher levels: tubes 8 and 9 registered almost 23.3 $\mu g/m^3$ from the passive tubes (placed at 3 meters altitude) and validated by the AQM station (placed at 4 meters altitude) in comparison to 61.2 $\mu g/m^3$ recorded by the Azimut station carried at human level (1.5 meters altitude) near these tubes. The biggest difference between fixed and mobile air pollution monitoring is showcased by the passive tube 4, which recorded an NO_2 concentration of 14.9 $\mu g/m^3$ in comparison to 74.17 $\mu g/m^3$ registered by the mobile station Azimut; this translated in a human-level pollution score which is almost five times higher than the official reported scores by the stationary monitoring devices.

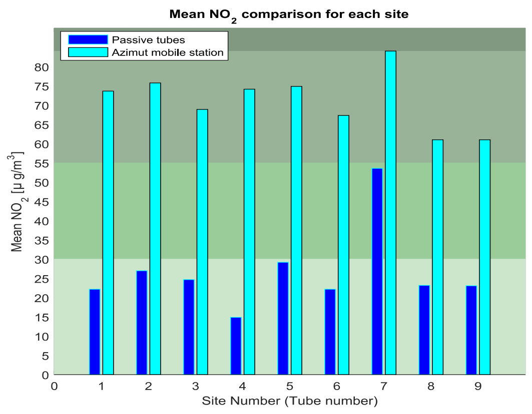


Fig. 11. *NO_2 pollution level registered by passive tubes versus the mobile station Azimuth carried at the human level.*

While various reasons and factors could be further taken into consideration for explaining the significant difference between the investigated emission levels, this finding brings a solid awareness towards the real impact that air and noise pollution can have on human health and the risk that citizens are facing when walking in extremely crowded and congested areas in the city.

5. Conclusions and future perspectives

This paper debates the topic of air monitoring using a combination of stationary versus smart and mobile pollution units which can be carried on a daily basis by citizens travelling in congested urban areas. Two experimenting protocols have been analysed by using: a) fixed passive tubes for NO_2 monitoring which have been verified against a reliable AQM station and b) smart and mobile sensors with real-time data transmission and collection. The proposed experimentation protocols not only show a significant higher impact of NO_2 concentrations when using smart sensors carried at human level and walking inside highly circulated urban areas, but also poor noise levels registered especially during evening peak hours. Weather conditions are also important factors to be used when analysing the pollution concentration due to their strong correlation and high temporal influence.

Limitations and perspectives

Besides the advantages and disadvantages of using each of the monitoring units detailed in Section 3.1, the main limitations for monitoring, investigating and evaluating air quality by using a crowd-sensed initiative consists in the evaluation of the data accuracy. While multiple sensing units are available for testing and usage, one needs to verify the accuracy of the mobile stations for calibration and validation purposes. We have further adopted another mobile sensing unit called the Smart Citizen Kit (SCK) [20] which has been used simultaneously with the Azimut station, for air quality monitoring and double validation of the findings. The data analysis and results are the object of a future investigation which awaits for Metropolis research approval. The duration of the monitoring could also be extended to longer periods which can be a true challenge due to higher costs involving both human resources, material acquisition, data processing and interpretation. Seasonality could also be included in the analysis when more data would become available, as in our previous studies [10].

Despite important advantages of using low-cost sensing units for measuring air pollution at a very granular city scale, various questions about the use and large-scale utilisation of such devices remain challenging and unanswered. Important aspects which are currently under investigation relate to the regulated production and marketing of such units, the use and ownership of the generated data, the cost of maintenance and installation, etc. But one important question concerns as well the electronic waste and the impact on public health [37], especially as many cities around the world are switching towards a sustainable and ecological paradigm [38].

The NGC project is further developing more studies on how to better integrate accurate air quality information with traffic congestion monitoring (see work submitted in [39]), but also how to involve citizens in an active crowd-source activity for raising awareness around pollution and traffic behaviour. Offering the correct monitoring tools will trigger more adapted actions which will improve on the long-term the life of inhabitants in such complex environments.

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7. References

[1] A. J. Krupnick, "Challenges to Managing Air Pollution," *Journal of Toxicology and Environmental Health, Part A,* vol. 71, no. 1, pp. 13-23, 2008.

[2] P. Kumar, S. Jain, B. Gurjar, P. Sharma, M. Khare, L. Morawska and R. Britter, "New Directions: Can a "blue sky" return to Indian megacities?," *Atmospheric Environment,* vol. 71, pp. 198 - 201, 2013.

[3] IARC, Air Pollution and Cancer, vol. IARC Sicentific Publications, International Agency for Research on Cancer, 2013.

[4] S. S. Lim, T. Vos, A. D. Flaxman and et.all, "A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010," *The Lancet* , vol. 380, pp. 2224-2260, 2013.

[5] M. Ruano, "Ecourbanism. Sustainable Human Settlements: 60 case studies," Gustavo Gili, Barcelona, 1999.

[6] H. Barton, "Eco-neighbourhoods: A review of projects," *Local Environment,* vol. 3, no. 2, pp. 159-177, 1998.

[7] M. C. T. Ministère de la cohésion des territoires, "Les éco-quartiers," 2016. [Online]. Available: http://www.cohesion-territoires.gouv.fr/les-ecoquartiers. [Accessed 05 01 2018].

[8] L. Dupont, L. Morel and C. Guidat, "Innovative Public-Private Partnership to Support Smart City: the Case of Chaire REVES," *Journal of Strategy and Managment,* vol. 8, no. 3, pp. 245-265, 2015.

[9] GN, "Nancy Grand Cœur," 2012. [Online]. Available: http://www.grand-nancy.org/grands-projets/nancy-grand-coeur/. [Accessed 05 01 2018].

[10] A.-S. Mihaita, M. Benavides and M. Camargo, "Integrating a mesoscopic traffic simulation model and a simplified NO2 estimation model," in *23rd World Congress on Intelligent Transportation Systems (ITSWC 2016),* Melbourne, Australia, 2016.

[11] A.-S. Mihaita, M. Camargo and P. Lhoste, "Optimization of a complex urban intersection using discrete event simulation and evolutionary algorithms," in *Proceedings of the International Federation of Automatic Control World Congress - IFAC WC 2014,* Cape Town, Africa, 2014.

[12] A. Plaia and M. Ruggieri, "Air quality indices: a review," *Reviews in Environmental Science and Bio/Technology,* vol. 10, no. 2, pp. 165-179, 2011.

[13] D. M. Stieb, R. T. Burnett, M. Smith-Doiron, O. Brion, H. H. Shin and V. Economou, "A New Multipollutant, No-Threshold Air Quality Health Index Based on Short-Term Associations Observed in Daily Time-Series Analyses," *Journal of the Air \& Waste Management Association,* vol. 58, no. 3, pp. 435-450, 2008.

[14] S. Elshout, H. Bartelds, H. Heich and K. Leger, "CAQI Air quality index, Comparing Urban Air Qualiy across borders," 2012.

[15] C.-Y. Chong and S. P. Kumar, “Sensor networks: Evolution, opportunities, and challenges,” *Proceedings of the IEEE,* vol. 91, no. 8, pp. 1247-1256, 2003.

[16] P. Kumar, L. Morawska, C. Martani, G. Biskos, M. Neophytou, S. D. Sabatino, M. Bell, L. Norford and R. Britter, “The rise of low-cost sensing for managing air pollution in cities,” *Environment International* , vol. 75, pp. 199-205, 2015.

[17] M. I. Mead, O. A. M. Popoola, G. B. Stewart, P. Landshoff, M. Calleja, M. Hayes, J. J. Baldovi, M. W. McLeod, T. F. Hodgson, J. Dicks, A. Lewis, J. Cohen, R. Baron, J. R. Saffell and R. L. Jones, “The use of electrochemical sensors for monitoring urban air quality in low-cost, high-density networks,” *Atmospheric Environment* , vol. 70, pp. 186-203, 2013.

[18] AQE, “Air Quality Egg,” 2016. [Online]. Available: http://airqualityegg.com/. [Accessed 05 01 2018].

[19] J. Gabrys, “Citizen Sense,” 2016. [Online]. Available: http://www.citizensense.net/. [Accessed 06 01 2018].

[20] SCK, “Smart Citizen Kit,” 2016. [Online]. Available: https://smartcitizen.me/. [Accessed 05 01 2018].

[21] Alphasense, “Alphasense air, Sensors for air quality networks,” 2016. [Online]. Available: http://www.alphasense.com/index.php/air/. [Accessed 07 01 2018].

[22] MIT, “Clarity, Department of civil and environmental engineering,” 2016. [Online]. Available: http://clairity.mit.edu/site/html/home.html. [Accessed 05 01 2018].

[23] D. E. Williams, G. S. Henshaw, M. Bart, G. Laing, J. Wagner, S. Naisbitt and J. A. Salmond, “Validation of low-cost ozone measurement instruments suitable for use in an air-quality monitoring network,” *Measurement Science and Technology,* vol. 24, no. 6, p. 065803, 2013.

[24] S. Moltchanov, I. Levy, Y. Etzion, U. Lerner, D. M. Broday and B. Fishbain, “On the feasibility of measuring urban air pollution by wireless distributed sensor networks,” *Science of The Total Environment* , vol. 502, pp. 537-547, 2015.

[25] A. T. Campbell, S. B. Eisenman, N. D. Lane, E. Miluzzo, R. A. Peterson, H. Lu, X. Zheng, M. Musolesi, K. Fodor and G. S. Ahn, “The Rise of People-Centric Sensing,” *IEEE Internet Computing,* vol. 12, no. 4, pp. 12-21, 7 2008.

[26] A. Kapadia, D. Kotz and N. Triandopoulos, “Opportunistic sensing: Security challenges for the new paradigm,” in *2009 First International Communication Systems and Networks and Workshops,* 2009.

[27] NIEHS, “Exposure Biology and the Exposome, U.S. Department of Health and Human Services, National Institute of Environmental Health Sciences,” 2014. [Online]. Available: http://www.niehs.nih.gov/research/supported/exposure/bio/. [Accessed 04 01 2018].

[28] US-EPA, “What Are the Six Common Air Pollutants?,” 2016. [Online]. Available: https://www.epa.gov/criteria-air-pollutants. [Accessed 05 01 2018].

[29] MEDE, “Bilan de la qualité de l'air en France en 2012,” 2012.

[30] ATMO, “La carte des AASQA,” 2016. [Online]. Available: http://bit.ly/2cjX6QX. [Accessed 05 01 2018].

[31] A. Lorraine, “ATMO Grand Est,” 2018. [Online]. Available: http://www.air-lorraine.org/. [Accessed 05 01 2018].

[32] LigAir, “Caractérisation des niveaux ambiants de formaldéhyde autour du site industriel,” LigAir, surveillance de la qualité} de l'air en région Centre, 2009.

[33] ATMO-Alsace, “Modélisation de la qualité de l'air sur le futur éco-quartier Danube,” Association pour la Surveillance et l’étude de la Pollution Atmosphérique en Alsace, 2012.

[34] Azimut, “FIREFLIES IEQ Azimut Monitoring,” 2017. [Online]. Available: www.azimut-monitoring.com. [Accessed 05 01 2018].

[35] B. Trousse, M. Palloth and C. Tiffonh, “Co-creating environmental services based on Pollution Citizen Sensing,” *Interdisciplinary Studies Journal,* vol. 3, no. 4, pp. 331-350, 2014.

[36] M. E. D. D. Ministère de l’écologie et du développement durable, “Arrêté du 22 juillet 2004 relatif aux indices de la qualité de l’air,” 2004. [Online]. Available: http://bit.ly/2Av37Gp. [Accessed 20 12 2017].

[37] K. Grant, F. C. Goldizen, P. D. Sly, M.-N. Brune, M. Neira, M. Berg and R. E. Norman, “Health consequences of exposure to e-waste: a systematic review,” *The Lancet Global Health,* vol. 1, no. 6, pp. e350-e361, 12 2013.

[38] B. Bayulken and D. Huisingh, “Are lessons from eco-towns helping planners make more effective progress in transforming cities into sustainable urban systems: a literature review (part 2 of 2),” *Journal of Cleaner Production,* vol. 109, no. Special Issue: Toward a Regenerative Sustainability Paradigm for the Built Environment: from vision to reality, pp. 152-165, 2015.

[39] A.-S. Mihaita, M. Benavides Orti and M. Camargo, “Predicting air quality by integrating a mesoscopic traffic simulation model and simplified air pollutant estimation methods,” *International Journal of Intelligent Transportation Systems Research,* vol. (under revision), 2017.

[40] A. Lorraine, “ATMO Grand Est, Lorraine,” 2017. [Online]. Available: http://bit.ly/2Cw0Qg5. [Accessed 18 01 2018].