Agency and responsibility in smart air pollution monitoring

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***Abstract*— In this paper, we use two cases to illustrate the role of citizens, researchers, and low-cost sensors for air quality monitoring in communal smart environments. In these settings, human-sensor collaborations might reconfigure relations between actors of Citizen Science and the political processes in the terms of roles, agency, and responsibilities. By looking at two cases run in Denmark and Norway, we strive to understand the roles played by citizens, researchers, and sensors in air quality monitoring, the responsibilities assigned to citizens and sensors in producing data about air pollution, and how the quality of the collected data was judged. The two cases show that low-cost sensors constitute an important driver for participation. By collecting data that can be used by local governments to derive relevant insights and informing action, citizens can be more actively involved in improving and maintaining the quality of their living environment. In both cases, we see the sensors as holding the potential to change the way citizens look at their living environments and facilitate data creation as a purposeful and meaningful social activity.**

Keywords—agency, responsibility, low-cost sensors, citizen participation

I. Introduction

Citizen science (CS) can be defined as the non-professional involvement of volunteers in the scientific process, commonly in data collection, but also in other phases, including data analysis and interpretation, problem definition and the dissemination of results [1, p. 2]. Geospatial intelligence can be gained from CS by using the data to validate and calibrate Earth observation (e.g., Copernicus) with lower cost and greater frequency. Combining CS with machine learning and other Artificial Intelligence techniques can extend scientific knowledge, as already proven in deforestation, agricultural production, and light pollution [1]. Thus, human–machine is a promising arena in CS, where humans and machines work "collaboratively" and share agency to perform tasks. The rapidly evolving capabilities of digital technologies (ranging from machine learning to sensors) allow augmenting humans or even taking over a broad range of functional tasks required to generate new knowledge. Integrating humans and machines in CS opens up new ways of collaboration between the two but also raises questions about the distribution of tasks and how humans and this type of technologies can complement each other to expand their respective skills. Likewise, questions of how such set-ups might reconfigure relations between actors of CS and the political processes that often use the knowledge produced by CS are of interest. In this paper, we use two cases in two Northern European cities, Aalborg in Denmark and Kristiansand in Norway, to illustrate the role of citizens, researchers, and Low-Cost Sensors (LCS) for air quality monitoring in communal smart environments. In these two cases, we set up projects in which citizens and researchers collaborated with LCS for data collection about air pollution (opportunistic sensing). We aim to describe and compare how technology has reconfigured the relationship between citizens, researchers, and local authorities in the two cases.

The two cases are part of the NordicPATH project (http://nordicpath.nilu.no), which explores new methods for using data derived from LCS through Urban Living Labs in the Nordic countries. A major objective of the project is to provide methods for engaging citizens and incorporating their inputs into planning processes, aiming for inclusive urban policy governance.

Although LCS have been used to monitor air pollution for quite some time, there is an apparent scarcity of cases where the data collected has been used for policymaking. Likely to be at play, according to the literature, are issues with the quality of data from such sensors due to challenges with reliability [2], sensor robustness [2], [3], measurement repeatability [3], as well as the lack of a standardization on how such data should be validated [4].

The use of citizen-collected data for environmental management also seems to present problems. The reason for this may be due to the monitoring design, for example. Also, there seem to be issues with citizens not getting data from monitoring to the appropriate decision-makers, a lack of trust in objectivity and credibility, and non-comparability due to factors like validation and calibration or data completeness [5]. The lack of metadata (such as, the position, location, and altitude of sensors, or the unit's age) can also pose a problem for air quality monitoring with LCS [6]. It is argued that this scepticism towards the validity of data collected by citizens in combination with an overall reliance on expert knowledge and viewing citizen science as related to behaviour change are important barriers for a more collaborative environmental management [7].

Previous literature also covers citizen engagement and the need of data infrastructures in sensor networks by bringing different subsystems into the same data architecture [8] that is managed and organized to be used by multiple stakeholders with different needs [9]. In participatory sensing, there is a need to foster stakeholders' collaborative practices [10] and enhance the possibilities of collective political action [11]. One of few examples covering more than one area is from the Netherlands, where a national platform is developed and implemented by combining data from official monitoring and LCS to "connect with citizens and their respective needs" [12, p. 18].

As of now, little is known about the integration between humans and machines, or the synergies or symbiosis that result from such integration, when citizens are involved in gathering air pollution data with the aim to inform urban policy. As one of the main goals of the NordicPATH project is to move from air pollution data collection to action as part of inclusive urban governance, we are interested in the interaction between citizens and local authorities when LCS for air pollution are used. Two case studies from the NordicPATH project will illustrate this.

Through the analysis of these cases, we aim to examine if and how data collection using LCS opens the possibility to rethink and reconfigure the relationship between citizens and local authorities. To achieve this aim, we address the following questions:

- what roles did citizens, researchers and LCS play in air quality monitoring?
- what responsibilities were assigned to citizens, researchers and LCS in producing data about air pollution?
- how was the quality of the collected data judged?

II. Citizen-Based Air-Quality Monitoring

A. Distribution of agency and responsibilities in citizen-based air-quality monitoring

Influenced by Science and Technology Studies (STS), we use an encompassing concept of agency that goes beyond human intentions and includes the agency of technologies to examine how citizens, researchers, and technologies interact to influence the course of events. Taking this view helps us conceptualize both humans and sensors as actors (those who act, as a participant in an action or a process) in air-quality monitoring. Therefore, instead of looking at citizens, researchers, and technologies (e.g., data, sensors, servers, sniffer bikes) as self-contained independent actors, we view them as entangled in a network in which both humans and technologies share agency, although not necessarily symmetrically, as human agency takes the lead in the formation of this network (e.g., they decide how the network is designed and how the data is selected).

When agency and responsibilities for collecting data are shared between citizens and technologies in these networks, not only is it possible to monitor air quality but also reconfigure the relationship between citizens and other stakeholders, particularly local governments. As Ponti and Craglia [13] pointed out, digital technologies hold the potential to change the way citizens look at the environment and facilitate data creation as a meaningful social activity. In turn, they also hold the potential to turn citizens into agents of change in the places where they live. Second, data that citizens generate in these monitoring networks may enable citizens to "achieve" citizenship. In fact, by collecting data, citizens can be encouraged to take up responsibility and help in solving urban problems. Third, data generated in these networks may not be as accurate as data produced for regulatory compliance. However, it could raise different concerns and possibilities useful to integrate the representation of reality provided by official data.

B. Human-Sensor Integration in Citizen-Based Air-Quality Monitoring

In collaboration with citizens, LCS are deployed to measure and map air quality, potentially enabling well-informed decisions and increasing awareness [14]. Previous studies show that citizens can passively collect data using LCS, without being involved in data analysis [15]. For example, Lim et al. [16] and Adams et al. [17] reported on projects aimed at sampling air quality: volunteers were equipped with AirBeam sensors and asked to sample several routes by walking or cycling. The tasks involved in passive data collection entail a low-level of complexity as collecting data of air pollution does not depend on the data collected by other volunteers. Regarding the background skills to perform these tasks, citizen scientists seem to need general/common skills, required in routine tasks, while researchers keep the role of data processing and analysis [18]. Citizens, however, have also been involved in forms of participatory sensing. A good example is citizen sensing in the European project Making Sense [19]. Pritchard and Gabrys [20] describe citizen sensing technologies as means "to provide a democratic corrective or challenge to the standard processes for monitoring environments, gathering data and acting on those data" (p. 335). They further argue that a collective potential in community monitoring can be reached when citizens participate and engage with perceptive and affective problem [20]. In MakingSense.eu [19], citizens' role was not restricted to data collection but included setting goals for the projects, sensing strategies and protocols for collecting data as well as participation in data analysis and discussion.

In spite of conducting passive data collection, it has been reported that citizens had a greater understanding of air pollution when they were able to host LCS devices [14]. In contrast to this, Tubridy et al. [7] expressed scepticism about citizen science data because of a "technocratic air quality management system" that relies heavily on official monitoring techniques and expensive monitoring technologies and conforms to narrowly defined institutional guidelines when gathering knowledge. A key reason for this is the importance of European Union (EU) standards in determining whether action needs to be taken to reduce air pollution (despite the fact that these standards are considered relatively lax and are significantly less stringent than those set by the World Health Organization [21]. The focus is primarily on ensuring that EU legal limits are not exceeded, not on preventing health impacts, according to a government advisor [7, p. 631]. Responsibility is a multifaceted concept in this context. As Uittenbroek et al. [22, p. 201] argued, in the context of urban climate adaptation, responsibilities encompass, among other elements, tasks, legal duties and accountability. Responsibility must, therefore, be unpacked explicitly as well as the tensions between these dimensions.

III. METHOD

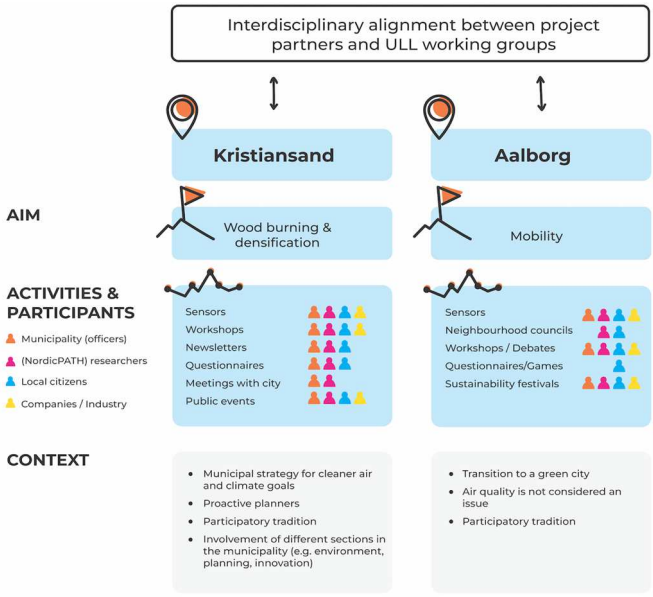
We present two descriptive case studies that benefited from the authors' direct experiences and involvement over a couple of years. Descriptive case studies are used to describe a phenomenon and the real-life context in which it occurred [23]. We selected these two cases because they complement each other and reveal similarities but also illustrate different challenges regarding, for example, capacity and sustainability. These cases illustrate citizens' gathering of air quality data using LCS as a source of evidence for taking measures about air quality.

Each case study describes the project and the role played by citizens, researchers, data, and technology. It also includes the strategies used to engage communities, build capacity and use the LCS.

IV. THE CASES: KRISTIANSAND AND AALBORG

The NordicPATH project's overall objective was to establish a new model for citizens' participation and collaborative planning. To do this, the intention was to apply a co-monitoring system and to promote a more inclusive planning process in both cases presented below and as it can be seen in Figure 1.

Fig. 1. The components in the two cases, Kristiansand and Aalborg.



The co-monitoring system were to combine environmental measurements from official monitoring stations and citizens' own measuring devices. The citizens were provided with two types of air quality measuring sensors; Airly sensors (static sensors hosted by citizens in their private dwellings) and sniffer bikes (mobile sensors attached to the private bikes of the citizens to monitor the air quality of the city while cycling). The more inclusive planning process were to involve citizens in the co-design of solutions to tackle environmental issues together with urban planners, authorities, and scientists. This was to be done by combining the use of more traditional analogue participation tools as workshops and focus groups with the use of digital tools, Public Participation Geographical Information Systems (PPGIS), to ensure a broad range of public involvement.

Air pollution is not isolated from the socio-economic situation, geography of an area, policy at local level, behaviour, preferences, etc. Thus, the combination of analysing data from LCS and data from participation tools help to understand how to improve the situation and to get a full picture of the situation in a specific socio-economic and environmental context.

A. Kristiansand

Situated in the south of Norway by the sea, Kristiansand is the sixth largest municipality by population in the country. The city is an attractive industrial hub with more people moving there every year. The municipality place great emphasis on sustainability and inclusiveness with initiatives such as 'A City for Everyone', where all the citizens can participate.

Environmental situation: The main issue addressed by the NordicPATH project in Kristiansand is wood burning, as a household heating system, since this city is characterized by seasonal air pollution. During winter the wood is burned mainly during evenings and on weekends. In winter days with low temperatures, low wind speeds and strong meteorological inversion, air pollution levels can reach high levels [24]

How the issue was addressed: The environmental issue was identified in collaboration with the city's municipality. Several citizens were provided with LCS (Airly sensors). They were chosen according to their location within three main areas, identified as places with higher pollution due to wood burning. Afterwards, data from the sensors was analysed by the NordicPATH researchers involved in the project. The collected data helped to further establish the spatial distribution of air pollution in the city. The data gathered by the scientists was translated into newsletters sent to the project participants to inform them about the air quality situation in their own neighbourhoods and to make them aware of the environmental situation.

Relationship between sensors and citizens involved: The provision of LCS to citizens increased their interest in Kristiansand's environmental situation. In terms of data, the LCS served as a tangible artefact to remind NordicPATH participants of citizens' direct involvement in improving air quality in their communities. As a result of the participants' emerging interest in air pollution, other local residents would become aware of the problem.

Methods to complement the data from LCS: Webinars were crucial to get citizens' interest in changing the environmental situation. The webinars were mainly informative but encouraged dialogue and interactions. For instance, in one of the webinars, Kristiansand fire brigade informed on how to start a fire in a more sustainable way. Another workshop invited members of the public to co-create actions to reduce pollution from wood burning. Data from LCS was also complemented with a PPGIS survey to better understand the insights from people, on residents' motivations about using wood burning as a central heating system, and attitudes to changing to other less polluting methods.

Quality of data, future policies and citizen engagement: The data from the LCS was used to 1) identify specific geographical areas of concern, 2) raise public awareness about the issue, 3) initiate actions by the municipality to include members of the public in discussing how the municipality

could act to help citizens reduce emissions from wood burning.

B. Aalborg

Aalborg is situated at the Limfjord in the northern part of Jutland, Denmark and is the fourth most populated city in the country. Aalborg is a great example of the post-industrial urban transformation that led cities to a deep transition. In the last decade, Aalborg has realized this transition from the 'city of the chimneys' into a city of knowledge and culture. The municipality has a great ambition to continue offering high living standards and a sustainable, healthy urban future.

Environmental situation: In Aalborg, not one single source of pollution has been of interest, but a relatively open position towards problematic issues was taken. In Denmark, air pollution monitoring is a state business, and the local planning authority was not inclined to make air pollution an issue, as long as EU threshold levels are kept. As the NordicPATH project were met with restraint from the municipal planners, neighborhood councils of the city were approached to find out if they were interested in data from air pollution and helping with monitoring. Some neighbourhood councils showed interest, especially in air quality related to traffic and wanted to collect data to help in their actions toward the plans of constructing a new highway close to the city.

How the issue was addressed: When the topic of interest was located, people in two neighborhood areas were approached to provide them with LCS. . The data collected from Aalborg has not yet been reviewed by data experts and translated into communication material directed towards citizens. The NordicPATH researchers responsible for the Aalborg case, made a few attempts to interpret the data with citizens, but with limited knowledge of data and the meanings of the different levels and their sources, the interpretation should be undertaken with high levels of caution. These efforts where made to accommodate interest from the citizens to know more about the data. However, a roundtable debate with project external experts on the Danish national measurement program, air pollution health researchers and a local politician was held with public access. The focus of this event was not the collected data from the project but the theme of air quality and related health issues as well as the benefits of citizen science measurements.

Relationship between sensors and citizens involved: The citizens in Aalborg who had a sensor installed showed interest in the data on several levels. Some were mostly interested in the data in its instrumentality towards a particular agenda that were of interest to them, e.g., increasing levels of traffic, while others showed a more general interest in the data. The later type of citizens were for example interested in why spikes occurred in the data and would try to relate spikes with events in their immediate surroundings, such as from woodburning or particularly dense traffic. The first type of people would not necessarily be interested in the different sources of pollution, unless this were related to their own agenda.

Both types of citizens would talk to their political network about the data and the measurements. However, the lack of understanding of the data were often a barrier to get the point across. The event with the external experts and the local politician showed that it is possible to affect a policy maker to become more aware and to 'want to do more'.

Methods to complement the data from LCS: Several meetings with the local neighbourhood councils were held throughout the project period, mainly to discuss citizen concerns about air quality and the project's progress overall. A round table debate was held as described. Several questionnaire surveys were also distributed, but in general a very low response rate resulted in limited use of these surveys.

Quality of data, future policies and citizen engagement: The data from the LCS was used to raise awareness about the issue to local policy makers, as described, however it is too early to say how successful this has been, as the adoption of policies is a longer process than the project period runs. The main impact of data collection lies in building capacity in the local neighbourhood councils. These councils are local political organs, elected by the inhabitants in the neighborhood and act as a link between citizens and the municipal administration. The data itself is not necessarily a political force as it needs to be interpreted within a specific context.

V. Discussion: Actors and Responsibilities

In this paper, we aimed to examine if and how data collection using LCS opens the possibility to rethink and reconfigure the relationship between citizens and local authorities. More specifically, we have striven to understand the roles played by citizens, researchers and sensors in air quality monitoring, the responsibilities assigned to citizens and LCS in producing data about air quality monitoring, and how the quality of the collected data was judged. By increasing our understanding of this topic, we are better equipped to support and enhance better synergies between the agents and develop communal smart environments for air-quality monitoring. We now discuss actors and agency, the role of technology, and the role of data in the two cases in relation to previous research.

A. Actors and the roles of citizens, policy makers, researchers and LCS in air quality monitoring

The NordicPATH researchers decided where to mount LCS, and citizens were not able to fully influence the location of the sensors. In Kristiansand, locations were chosen from the citizens agreeing to have a sensor mounted at or by their houses. In Aalborg, citizens suggested locations to mount sensors in the city. In both cases, citizens were able to collect air pollution data by sniffer bikes. Unlike the case of Aalborg, the municipality in Kristiansand was active in the process of designing co-monitoring and co-creation activities. In Kristiansand, the use of technology thus facilitated the local government to act and to involve citizens in the process. This was not only due to the NordicPATH project, but also to an intention from the policymakers to involve citizens. The human-technology integration can therefore be said to facilitate an ongoing reconfiguration of the relationship between policy makers and citizens.

On the contrary, the policy makers in Aalborg were not involved in co-monitoring activities but in project activities, such as workshops and the round table debate. The role of technology is thus difficult to assess in terms of reconfiguration of relationships. The main influence the data collection effort has had is in relation to the capacity building of actors in the local neighbourhood councils who, to some extent, were "educated" through participation in collecting data and meeting with project partners, in the importance of

good air quality. As these councils act as a link between citizens and local administration and politicians the awareness amongst this group of actors is of importance.

In Kristiansand, the NordicPATH researchers were involved in all activities of the project, as facilitators and supporters of the municipality's intentions. In Aalborg, on the other hand, the NordicPATH researchers were very active in finding citizens willing to act, talking to citizens about the project and the air quality issue in general.

The role of technology: The predefined role of LCS was to engage citizens by collecting data about air pollution. In that sense, the technology's role was to ignite action and promote agency. The two cases from the NordicPATH project shows that LCS constitute an important driver of participation, by giving citizens the opportunity to generate data on air quality. From the point of view of participants' engagement, collecting data has made it possible for them to be enrolled as sensors and monitors. By collecting data that local governments could use to derive relevant insights and informing action, citizens can be more actively involved in improving and maintaining the quality of their living environment [13]. Generating data can offer the opportunity for citizens to raise and amplify their voices within democratic processes at the local level of government [25]. Indeed, the role of LCS in Kristiansand was also to collect data to identify geographical areas of concern and to confirm the air pollution modelling done by local authorities. While we did not examine the complex matrix of social and technical dependencies in citizen data collection, LCS seem to act as 'focal devices' [26]. This means they hold the potential to change the way citizens look at their living environments and facilitate data creation as a focal practice, a purposeful and meaningful social activity [15].

B. *Agency and responsibilities assigned in producing data about air quality monitoring*

We can see that citizens in both cities were expected to become involved in air pollution issues and to act accordingly based on data. In Kristiansand, the local authorities wanted this responsibility to include, for example, a change towards responsible household heating and for citizens to participate in co-creating municipal actions to reduce household emissions from wood-burning. In Aalborg, the production of air quality data was not done by local authorities but by citizens in particular neighbourhoods in collaboration with NordicPATH researchers. The data from LCS were to be used towards specific agendas of interest in some local communities, while in other cases the interest in the data was more general and open. Here, the citizens wanted the NordicPATH researchers to help them protect their neighbourhoods by providing data from the sensors, thus pushing the responsibility towards the NordicPATH researchers in Aalborg.

The role of technology: The responsibilities of LCS in the NordicPATH project were to provide hyper-local data to ignite action. In Kristiansand, the aim was to ignite action from all stakeholders involved. In Aalborg, monitoring with LCS was used by citizens to raise awareness of local air pollution conditions to local policy makers.

While data and technologies in the two cases place responsibilities on local governments who have a role to play in fixing air quality problems, they also redistribute responsibilities onto citizens – to take more responsibility for air quality in their localities. Therefore, collecting data becomes a way of taking up responsibility as individual citizens. Especially in similar projects on environmental issues, technologies and data should not be seen as prescriptive but "as transformative forms of engagement, influencing participants' identities, motivations, and perceptions about the environment" [27, p. 10].

C. *The role of data and how it was judged*

Both cases serve as examples of data having the role to create agency. Policy makers in Kristiansand used data to engage citizens to make a change and people from the neighbourhood association in Aalborg wanted to use data to influence policy makers' plans of a new highway. This is in line with previous research [13], [14] [20]. In Aalborg, policy makers were not interested in using LCS since they are not having the official responsibilities to do so. This is an example of the effects of EU directives, and similar to suggestions made in previous research [22]. On the contrary, data in Kristiansand was judged by policy makers as complementing the official monitoring. This integration of data sources can be seen as a fruitful way to use and judge data, as also suggested in previous research [28]. Citizens in Aalborg struggled with interpreting the data and wanted the NordicPATH researchers to inform them about the value of data in relation to air quality. Accordingly, the role of data, for them, was not to enable well-informed decisions on an individual level [14], but rather to collectively, and in line with [20], pursue a democratic endeavour to protect their neighbourhood. The municipality in Kristiansand also wanted to pursue a collective democratic endeavour; to find solutions to the wood-burning issues by co-creating them with citizens in the most affected neighbourhoods.

Through the two cases, both combining co-monitoring with participatory activities, we see a collective potential of political capacities reached through engaging citizens in issues that involved "affective grappling and collective encounters with problems brought about by existing practices in the attempt to forge new political capacities." [20, p. 368]. However, the relationships were configured in different ways. In Kristiansand, the distribution of LCS to the public enabled the municipality to redistribute the responsibilities of lowering emissions from wood-burning to the citizens. In Aalborg, local neighbourhood councils developed their own political capacities through the NordicPATH researchers as air quality monitoring was not high on the municipality agenda.

VI. CONCLUSION

Based on the two cases from the NordicPATH project, we conclude that LCS constitute an important driver for participation with a collective potential of political capacities. By giving citizens the opportunity to generate data on air quality that local governments can use to derive relevant insights and informing action, citizens can be more actively involved in improving and maintaining the quality of their living environment. LCS are seen as holding the potential to change the way citizens look at their living environments and facilitate data creation as a purposeful and meaningful social activity. This is seen in the two cases, where the role of technology and relationships between stakeholders are different from what is 'pre-defined' in policy documents and the practice of official monitoring.

Rather than imposing a technocratic approach to data to ensure EU legal limits [7], the legal duties and accountability of local governments [22] could also be focused on preventing health impacts. A participatory approach in combination with a focus on preventing health impacts can enable capacity building and the redistribution of responsibilities and agency among stakeholders. Further research could focus on exploring the barriers and bottlenecks of citizen participation and collaborative urban and environmental planning.

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