Particles Matter: A Case Study on How Civic IoT Can Contribute to Sustainable Communities

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ABSTRACT

This case study reveals how the Civic IoT project Luftdaten.info, though being organized within limits of technical equipment, resources, and academic knowledge, can contribute in multiple ways to more sustainable cities or communities: (1) People become aware and engaged for their local environment, and some change their behavior, (2) the project itself is managed in a sustainable way, (3) the publicly available data on particulate matter (PM) influences the local public sphere. Explored by a media content analysis and two expert interviews, the PM topic in Stuttgart can be characterized as a discursive long-term process. Nevertheless, a data map comparison shows how easily misunderstandings can occur caused by data analytical and visualization decisions. Finally, this study supports Meadows' idea that "[a]ll people and institutions play their role within the large system structure" but as Luftdaten.info shows, it is not only "industries, governments, environmentalists, and most especially economists [playing] essential roles in contributing to sustainability" it can also be ordinary, tech-savvy people making the first essential steps.

CCS CONCEPTS

• **Human-centered computing** → **Empirical studies in collaborative and social computing**; *Computer supported cooperative work*; **Visualization design and evaluation methods**; • **Applied computing** → **Sociology**.

KEYWORDS

Social IoT, Civic IoT, Sustainable Smart Cities and Communities, Sensors, Particulate Matter, Data Maps, Governance, Public Sphere

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1 INTRODUCTION

Recent developments around Sustainable Cities and Communities have shown how sensor technology can be leveraged for environmental monitoring, e.g. [8] [13]. The research field "Social Internet

of Things" (SIoT) contributes a more human-centric perspective that does not only focus on the devices or sensors but on a network of people applying the IoT [20]. In the Citizen Science project "Luftdaten.info", an SIoT sensor network is applied for environmental monitoring. Founded in the German city Stuttgart in 2016, the project is dedicated to measure particulate matter (PM), i.e. particles of e.g. dust, rubber, liquids, that remain suspended in air. Luftdaten.info represents an interesting case to the LIMITS community as it leverages easy-to-use but limited sensor technology on a voluntary community basis, that is limited by funding and initial knowledge. In this paper, Luftdaten.info is theoretically founded on the concept of Civic IoT [14], which shall be extended by focusing on sustainability.

Sustainability is here understood as a multi-disciplinary and complex concept that is not limited to environmental sustainability. Sustainability is not a physical unit that can be easily measured, rather, it is constructed by discourse which means that people from different branches can interpret sustainability in various ways. Consequently, there can be various beliefs on which measures are beneficial for sustainability. This study is inspired by Meadows' 2030 vision for a sustainable future [16], to which Luftdaten.info provides multiple connections, especially regarding the following claims: (a) "efficient, closed-loop materials systems", (b) "flexibility, innovation (social as well as technical), and intellectual challenge. A flourishing of science, a continuous enlargement of human knowledge", (c) "decentralization of economic power, political influence, and scientific expertise", (d) "media that reflect the world's diversity and at the same time unite cultures with relevant, accurate, timely, unbiased, and intelligent information, presented in its historic and whole-system context."

Applying methods from empirical social sciences to a research object of computer science, this paper examines sensor technology-based data creation within the limits of technical equipment, resources, and academic knowledge that Luftdaten.info is facing. Doing so, the overarching research question of this study is "How can Civic IoT contribute to sustainable cities and communities?", and the following contributions are provided:

- (1) Analyzing Luftdaten.info's compliance to various goals of Computing within Limits by dissecting the project's social, ecological, and economic sustainability.
- (2) Examining the real-world implications of Luftdaten.info and its limits, namely towards media coverage, local governance, and public information.
- (3) Illustrating the limits of PM data communication in a comparison of two maps communicating the same input data in different ways.

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The paper will not contribute to the ongoing discussion on the technical reliability of low-cost PM sensors or the value of citizen science projects for research and development or governance per se.

The remainder of the paper is structured as follows: In section 2, the background introduces the Stuttgart area, the PM topic, and Luftdaten.info. In section 3, related works in the fields of Computing within Limits and the Social Internet of Things are presented. In section 4, the methodology and study design is summarized. In section 5, empirical findings are described and discussed. The paper finishes with a conclusion and outlook in section 6 by framing the findings and its interpretation back to Meadows' vision.

2 BACKGROUND

2.1 Particulate Matter and the Stuttgart Area

Particulate matter (PM) can be distinguished between natural (like Saharan dust) and human-made PM, and between primary particles (emitted directly into the atmosphere from combustion sources) and secondary ones (formed by chemical reactions in the air) [4]. The Stuttgart Environmental Office lists traffic as main source of PM due to causing tire and brake wear, and engine and other emissions; second, it is heating and third, industrial pollutant sources causing higher PM values [3].

The discourse around PM in urban areas illustrates conflicting interests around sustainability. Even though PM has a clear unit that measures particles in $\mu\text{g}/\text{m}^3$ and widely agreed categories of fineness (i.e. PM_{2.5}, PM₁₀), the public communication of such values for local neighborhoods comes together with many social issues. By referring on air pollution data, personal life styles are increasingly criticized, e.g. driving highly-motorized cars, lighting ambiance fireplaces, or taking the airplane for short trips. Public discussions on PM tend to heat up quickly as criticized people might feel limited in their personal freedom. Nevertheless, the negative impact of PM on people's health cannot be neglected. It is estimated that in Germany in the period 2007-2015 an average of about 44,900 premature deaths per year were caused by particulate matter [21].

In Germany and especially in Stuttgart, where the headquarters of Mercedes-Benz/Daimler and Porsche are located, the PM topic is closely related to the local political economy. The criticism around urban air pollution is partly conflicting with the highly productive car industry. With regard to employment and public revenues, the city government on the one hand has no economic interest in reducing the automotive industry or criticizing car drivers, their consumers. On the other hand, the city government has to ensure public health and act in the interest of citizens.

2.2 Luftdaten.info

Luftdaten.info is a bottom-up project developed within the framework of the Open Knowledge (OK) Lab Stuttgart. The core team is located in the German city Stuttgart while other projects members and contributors are distributed over the world. The German word "Luftdaten" translates to "air data". Luftdaten.info collects citizen-sourced sensor data on PM by providing a low-tech sensor kit and an open environment.

Luftdaten.info resulted from the "Code for Germany" program of the Open Knowledge Foundation Germany. The aim of the program

was to promote developments in transparency, Open Data and Civic Tech in Germany. The Labs are regional groups of designers, developers, journalists and other people meeting regularly to work on applications around Open Data [15]. In early 2015, motivated tech-savvy citizens started the project dedicated to collect sensor-based PM data by local people with help of do-it-yourself sensor kits. Once started from the Stuttgart area, thousands of people around the world installed self-built sensors on the outside of their homes or workplaces until today.

From the transmitted data, Luftdaten.info generates a continuously updated, publicly accessible and intuitively understandable map visualizing the PM concentration. Luftdaten.info has significantly grown over the last years to a worldwide data map. The project will soon be renamed to "Sensor Community" to emphasize the international character of the project.

3 RELATED WORKS

Clean air itself is common good that people especially residents care about, polluted air is often times an indicator for resource consumption, e.g. heavy traffic. In the field of Computing within Limits, Ziegler [23] worked on an approach to govern the limited commons by computing applications. He emphasized that technologists should adopt "participant-led research methods that leverage local communities' expertise about their own environments, social institutions, and cultural norms" in order to "achieve the best environmental outcomes". Luftdaten.info complies to this approach as labs with local people were set up to develop applications for the local issue, air pollution.

Environmental monitoring leveraged by communities or engaged citizens has been researched by Pargman, Joshi, and Wehn [18] analyzed the potential of Citizen Observatories to form publics for management and stewardship of natural resources at the example of water quality management from a citizen science perspective. While the authors studied the potentials of public management organized by citizens in a direct way, this study will shed light on more indirect ways how an civic initiative like Luftdaten.info, by raising worldwide awareness on the PM topic, might have effects on local public spheres and governance, as well as on individuals' behaviors.

Next to environmental and social aspects, the technical infrastructure of such IoT applications needs to be perused. Hazas, Morley, Bates and Friday [11] have discussed the tremendous growth of streamed internet data since the last decade and raised concerns regarding current forecasts suggesting that the data appetite is going to increase even more. Especially the development of the Internet of Things (IoT) or machine-to-machine-communication would be said to create a large data traffic that might overstrain today's energy suppliers. The authors point out that IoT devices differ in terms of their communication footprint and that the initial embodied energy costs of a device need to be balanced by the potential energy savings of their application.

Likewise, Pargman and Wallsten have raised concerns regarding the world's resource scarcity and call for "developing a suitable infrastructure and a "sufficient" level of service so as to guarantee the largest functionality for the lowest cost and the greatest number of people for the longest possible duration both within and between

countries." [17]. Both endeavors, a low communication footprint and a durable project set-up that maximizes its outputs, are ascertained in this paper.

The Social Internet of Things (SIoT) is understood as connected things having social properties emerging with their services and by relating humans and devices with each other [7]. In a recent book by Soro, Brereton, and Roe [20], SIoT is described as a much broader concept than the initial business- or industry-driven developments around the Internet of Things (IoT). Today, IoT devices are ubiquitous at our homes, workplaces, and public places, in our cars, or on our bodies [20]. It remains an open question, if such devices though ubiquitously used are beneficial or harmful for civic purposes and sustainability.

Recently, SIoT has been rethought in a way that emphasizes the role of IoT-technology for civic purposes. This paper follows the conception of a Civic IoT described by Lui, Balestrini and Vilaza [14]. The authors collected several IoT-based applications aiming at a specific civic goal. Applying the Civic IoT taxonomy proposed by the authors, Luftdaten.info can be categorized into the following items:

- Addressing matters of concern, i.e. observing particulate matter (PM) in the Stuttgart region;
- Building communities, i.e. regular community meetings and workshops;
- Inviting citizen participation, i.e. offering citizen meetups, Open Source, Open Data, do-it-yourself sensor kits;
- Rising awareness, i.e. communication of PM data in Stuttgart and media work.

In this way, Civic IoT combines technical innovation with a civic goal. As for this case study, Luftdaten.info created a large societal, technical, and communicative output with innovative but limited means: Being a voluntary-based, crowd-funded do-it-yourself community, the core team needs to work very efficiently without consuming much material, budget, or time of the participants. How they are organizing themselves and what sustainable computing projects might learn from Luftdaten.info is elaborated in the following sections.

4 METHODOLOGY AND CASE STUDY DESIGN

This study applies an open methodology approach, which means that the first findings led to decide on the next methodological steps. Such an exploratory multi-method design suits well for young and interdisciplinary fields like Civic IoT and Computing within Limits to gain an in-depth understanding of the case.

First, Luftdaten.info is analyzed regarding their awareness and actions towards a sustainable project management taking into account ecological, social, and economic sustainability (see section 5.1). Two expert interviews of in total 150 min served to receive a detailed image of how Luftdaten.info could contribute to a more sustainable city or community. The interviewees are: an administrator of the Luftdaten team, and a local newspaper journalist from Stuttgarter Zeitung (StZ) responsible for the coverage of the PM topic and data journalism. From these findings, a more general discussion on chances and risks of environmental IoT data for public information is given (see section 5.3).

Second, the interview data together with a media content analysis gives insights on Luftdaten.info's implications on the local public sphere and governance (see section 5.2). The quantitative content analysis comprised a search of all online articles from 2010 to 2019 containing the term "Feinstaub" (engl. fine dust) and allows to estimate the importance of the PM topic in the Stuttgart news over time.

Third and last, the online services from Luftdaten.info and the StZ have been examined. The PM data is visualized and communicated via two different data maps based on the same input, the "Luftdaten" (engl. air data) map by Luftdaten.info and the "Feinstaubradar" (engl. fine dust radar) by StZ. Both maps are compared and critically discussed (see section 5.4).

5 FINDINGS AND DISCUSSION

5.1 Sustainability Management of Luftdaten.info

5.1.1 Ecological Sustainability. The Luftdaten team is "certainly concerned that [their] project does not become a bigger environmental problem than it can solve." (Interviewee A, "Luftdaten.info" administrator) which is why, they would care about other side effects next to clean air. One approach is working on decreasing the CO₂ pollution by using the data to "find out how to better solve heating problems or how to structure traffic differently." (A) To this end, Luftdaten.info tries to receive a maximum of insights from their collected data. In 2019, a Data Science Challenge took place at the University of Rostock to develop new approaches to use air data [22]. Such events would be beneficial to generate new knowledge. For this reason Luftdaten.info would be constantly looking for opportunities to collaborate with researchers and developers.

Regarding hardware production, the use of sensor technology necessitates to order devices from China as IT devices are almost not produced in Europe anymore. To the long distance shipping and the caused emissions, Luftdaten.info has a pragmatic attitude: "We [...] know that this is not optimal, but we don't feel too bad about it [...] as] our small direct mailings are used to fill gaps in containers." (A) The transportation of their goods would hence not pollute the environment much more. "With our cooperation partners we try to bundle shipments so that not so much has to be sent back and forth." (A) For group workshops, they would make collective orders to save delivery tours to private households. In this way, Luftdaten.info minimizes pollution caused by transportation and delivery of devices.

To keep hardware parts and their power consumption at a minimum, the Luftdaten team considers modular designs and interoperability. They made sure that their "technology has no unnecessary gimmicks [and] that the power consumption is low." (A) Further optimizing the resource consumption to the technical limits, the sensor boxes can use the present infrastructure, i.e. installed WLAN, to communicate the data. Moreover, Luftdaten.info would be thinking about installing additional sensors to their kit rather than building new devices, e.g. adding CO₂ sensors for indoor usage.

In terms of recycling, the Luftdaten team is organising the reuse of technology parts. As long as the kit is not defective, "we offer people to send us the device if they don't want to use it anymore. We check what still works and try to use it in new devices." (A) However,

the reuse is limited by the lifetime of the components e.g. the PM sensors had an initial lifetime of about 1 year. By applying software, the lifetime was successfully exceeded to 5-7 years (depending on its location and weather conditions). Beyond, the Luftdaten team regularly reminds their community to give electronic parts to a recycling center.

5.1.2 Social Sustainability. Concerning technology and operations, the Luftdaten team founded an association end of 2019, into which all donations flow. Prior, the funding was done through the Open Knowledge Foundation (OKFN). By now, Luftdaten.info aims at becoming independent. In this way, continuity could be maintained and would not depend on individuals running a server.

Luftdaten.info became an international project. Numerous groups in larger cities have built a local community for PM measurements. The team observed that their do-it-yourself approach has a positive effect on the long-term goal of the Luftdaten project: "[...] because people assemble the sensor kit themselves, the motivation to operate it in the long-term is quite high." (A)

Community members would be mostly people interested in either one of the topics, Air or Electronics. Nevertheless, the community is highly inclusive due to their open data, do-it-yourself, and citizen science approach. Members are placed all over the world: "[N]ow after three years we have 10,000 sensors in 60 countries" (A) representing all ages, gender, and educational backgrounds. "[F]rom a 14 year old boy from Taiwan, who put online a video assembling the sensor kit with his dad [5], up to a 70-year-old who proudly told me that he had made run the sensor at his age." (A) Luftdaten.info is moreover engaged to outreach and student education. In 2019 together with IBM, the Luftdaten sensor kit was assembled in a workshop by 250 school students in Berlin [6].

5.1.3 Economic Sustainability. The general expenses of Luftdaten.info are rather low since the community consists of volunteers who buy and assemble their sensor kit by themselves. The basic infrastructure would cost about 100-120 EUR per month and be financed by the core team which consists of 6-8 people depending on their availability. Ongoing fundraising campaigns via Betterplace ask for donations of about 1,500 to 2,000 EUR per year. In the last years, these campaigns "worked out quite well." (A) The team also runs other donation campaigns to integrate new sensors, hardware, and servers for additional data.

The Luftdaten core team regularly looks for collaborators, but there would be many issues finding the right partner: "For us, it is extremely important not to be pushed into a political corner." (A) Cooperating with a local automobile manufacturer or supplier would make the impression that Luftdaten.info would present biased data. While cooperating with an organization like Greenpeace, BUND (engl. Friends of the Earth Germany), Deutsche Umwelthilfe (engl. Environmental Action Germany), the accusation would come up of being against the automobile industry, or the industry itself. A partner from the software sector could be an option, e.g. IBM, Google, or Amazon, but Luftdaten.info hesitates because such companies would also be competitors in terms of data innovations. "Regarding Google, we are afraid that if we contact them, doing something innovative, they would take over the whole project. Also it is questionable whether we are still credible when being managed

by Google. [...] Many support us just because they know that we are ordinary people and not some big company." (A)

For the long-term perspective, Luftdaten.info seeks for public funding. Various funding programs would suit the project, for example public funding of the European Citizen Science Association at European Union level; but such would be highly competitive. At German federal level, the team is uncertain where to turn to, lacking contacts and expertise: "[W]e would not really know which ministry to contact at the moment." (A) The Luftdaten team is currently discussing the possibility of joining forces with international organisations in the field of education, for example with the Wikimedia Foundation.

The option favored by Luftdaten.info would be a public mandate to collect PM data in the public interest. In this way, the team hopes to work on the technology and the data gathering without obligations in political directions, perhaps similar to the German Weather Service. "Maybe they can take us under their roof, but I think their budget is also very limited." (A) In future, the Luftdaten team has hope for the new field of Citizen Science and potential public funding.

5.2 Real-world Implications of Luftdaten.info

Figure 1: The frequency of media articles on particulate matter (PM) in the local news medium Stuttgarter Zeitung increased between 2010 and 2017, and decreased since 2018. Data collected from <https://www.stuttgarter-zeitung.de/suche> search using the keyword "Feinstaub" (engl. Particulate Matter).

5.2.1 Local Public Sphere and Governance. The quantitative media content analysis of the Stuttgarter Zeitung (StZ) reveals that from 2015 to 2017 the local coverage on PM strongly increased (see Figure 1). This increase is an indicator that the PM topic became more and more relevant to the Stuttgart public and citizens, it seems to correlate with the founding year of Luftdaten.info in 2015. However, the StZ articles dedicated to Luftdaten.info appear only rarely: 1 article in 2015, 2 articles in 2016, 3 articles in 2017, 1 article in 2018, and 1 article in 2019.

Such discrepancy between the frequencies of media coverage on PM and on Luftdaten.info suggests that external events led to the increased importance of the PM topic in Stuttgart's local medium. The analysis reveals that in 2016, the city of Stuttgart has installed

a public alert called "Feinstaubalarm" (engl. Fine Dust Alert) as a reaction to a dunning letter from the EU. When activated, the alert interdicts the use of firesides at home and urges commuters to voluntarily use the public transport instead of cars. To increase the impact of the alert, transport services offer several reductions for subscribers.

In 2017, the media agenda shows that the civil society in Stuttgart became highly mobilized resulting in several protest actions and demonstrations to create more public pressure. However, the peak in 2017 (see Figure 1) can best be explained with the start of StZ's own data map service. The "Feinstaubradar" (fine dust radar) is a data journalism innovation based on the Luftdaten.info open data. Together with the map, StZ developed an automated journalism application that produces machine-written articles for the districts of Stuttgart and informs the public on currently measured PM values. In this way, the amount of articles related to PM is much higher than before.

Interestingly, the StZ journalist stated in the interview that the PM topic did not become much more relevant in Stuttgart because of the Luftdaten project: "It's not as if the Stuttgarter Zeitung hadn't reported on the topics of particulate matter and air quality before, and the topic was already highly emotional in 2017 [...] and] already has a long history in Stuttgart." (Interviewee B, journalist Stuttgarter Zeitung) However, the StZ radar would not exist without the openly accessible data from Luftdaten.info. In this way, the implication of Luftdaten.info on the local public sphere is that data-driven media services have been developed and provided to the public. Hence the public is informed with the help of sensor data and the data is presented to a much larger public than before.

Luftdaten.info is still struggling with being understood as an activist organization. According to the StZ journalist, the role of the Luftdaten project for local governance can be estimated rather low. He states that "The OK Lab people are activists with a very clear political agenda: open data and better air." (B) Luftdaten.info would might have stimulated a few local people becoming more engaged in these topics, however there would be still "many open questions regarding the generation of PM and which parts of people's lives are responsible for it." (B). However, the Luftdaten admin sees the role of their project as a neutral activity, and not being activists. The project would be dedicated to PM data collection and transparency: "We would like to position ourselves rather neutrally, since we are acting rather in the background. We would like to capture and aggregate the data and also provide it to the public. By working on this goal, we have found out that the [PM] subject is not so simple." (A)

It appears that Civic IoT projects like Luftdaten.info can play a role for local governance merely in an indirect way. From the insights of the interview, Figure 2 has been developed to summarize the observed implications of an Civic IoT project like Luftdaten.info on media and journalism as well as on governance. Even though, the here studied issue of high PM values has already been much reported by local media, the openly accessible data from Luftdaten.info increased the visibility of the PM issue even more, since the local medium StZ created a new data-based journalistic outlet, the StZ radar. In this way, public pressure is put on governance actors and the Luftdaten project becomes better known by the public. A direct contribution of Luftdaten.info to the local governance has

not yet happened since the image of being activists still seems to be prevalent. Reorganizing Luftdaten.info as a pure citizen science project, e.g. on such a platform [1], together with a public mandate and funding could be a promising way to be utilized for future governance.

Both interviewees see a heated public PM discourse in Stuttgart that makes it difficult to find consensus. Civic IoT data applied in a scientifically proven model to measure PM in communities, perhaps by collaborating with universities or other research institutions, could serve as data-based evidence to find consensus for future regulation.

Figure 2: This Civic IoT model has been developed based on the insights from the expert interviews. It shows how Civic IoT can indirectly play a role for local governance to tackle a community issue, either via media or citizen-scientific knowledge generation.

5.3 Environmental IoT-Data for Public Information

According to the interviewed journalist, it is difficult to say if the value of a data-based argument weighs more than a person's statement. However he "would tend to believe the data rather than the resident" because "experience has shown that, especially when it comes to environmental issues that can be measured well with sensors, perception is often shaped by personal circumstances or opinions." (B)

The low-budget Luftdaten.info sensor kits, available for about 30-40 EUR, allow to operate numerous more measuring points. Compared to the seven official PM measuring stations [2] that each

cost about 300,000-400,000 EUR, the low budget sensors can hence be installed at a much larger scale. The many sensor data collection stations create a long-term database which provides evidence for PM related statements. "At least I can check [with the data] my theory where the fine dust might come from [...because] [s]uch a wide-area data map moreover allows to recognize PM hotspots." (A)

However, data is not always as objective as it seems. Data is intentionally collected, designed and communicated. The StZ journalist reported that once a resident called him to complain about the Feinstaubradar map that would give a wrong impression on the air quality in his district called Birkach. After the journalist explained how the map is designed, the resident replied that he would hang 10 sensors and on the greenery in his district to improve the PM values shown in the map.

The complaint by the resident shows multiple issues that come across with Civic IoT and the communication of such sensor data. First, it is problematic that community members can hang their PM sensor in arbitrary places. In the worst case, they could try to manipulate the Luftdaten.info project itself. Second, the complaint illustrates how the communication of PM sensor data can be wrongly interpreted.

The map service "Feinstaubradar" created by StZ is based on the Luftdaten data. This means for the Stuttgart region, two PM data maps apply the same input sensor data, but show numerous differences in terms of data cleaning, processing, and visualization, which can lead to misunderstandings.

5.4 Same Data, Two Maps: A Comparison

The two data maps, Feinstaubradar by StZ and the Luftdaten map, show significant differences in terms of (1) area coverage (shapes of units), number of sensors per covered area, and zoom options, (2) scale and legend colors, and (3) data analytical design. Figure 3 shows how the design and communication decisions create different maps that could lead to varying interpretations.

(1) The upper images show the wider Stuttgart area which is the initial area of the Luftdaten project as well as the area range of the StZ. While the zoomed-out Luftdaten image (upper right) shows hexagonal structures aggregating the data of single sensors laying below, the zoomed-out Feinstaubradar image (upper left) divides the map into administrative districts and aggregates the sensors located in each district. By zooming into the Stuttgart city center in the Luftdaten map, the hexagonal structures is splitted up to the level of single sensors (lower right), while the impression of fully covered districts remains in the Feinstaubradar (lower left). The uniform coloring of the entire district implies complete sensor coverage, although some districts have large areas with no sensor installed.

(2) A look at the scales and their colors shows that the StZ radar only visualizes PM values from 0 to 80+ $\mu\text{g}/\text{m}^3$, whereas the scale of the Luftdaten map ranges from 0 to 500 $\mu\text{g}/\text{m}^3$. Both maps highlight the official limit of 50 $\mu\text{g}/\text{m}^3$ by changing the color of the scale. The StZ radar chooses rather light colors from a yellowish green (scale min.) to a yellowish violet (scale max.) that blur the expressiveness of the data map. In contrast, the Luftdaten map uses darker colors ranging from a blueish green (scale min.) over a deep red (about

75-100 $\mu\text{g}/\text{m}^3$) to a dark violet (scale max.). The choice of colors implies certain intentions of the map creators: While the Luftdaten map emphasizes such values lying by far over the official limit using an alerting color, the StZ radar chooses rather neutral colors that do not imply alerting values. It appears that the radar might downgrade very high values of more than 100 or 200 $\mu\text{g}/\text{m}^3$ since such would be visually summarized in the color of 80+ $\mu\text{g}/\text{m}^3$.

(3) The Luftdaten map and the StZ radar, both technically using the same Luftdaten input data, apply different data analytical designs to publish and communicate the aggregated sensor data. While Luftdaten.info uses the median and single sensor values for their map service, the StZ radar uses the average of aggregated sensor data. The average is characterized by being highly influenced by outliers, whereas the median is a outlier-stable figure. To compensate this potential influence by outliers, the StZ radar carries out a multi-step analytical scheme for their map service: Every 5 minutes, they query the real-time values of all sensors for Stuttgart and the surrounding area. Then, they use static rules to calculate hourly PM values. "For example, if one sets the radar on 10:00 am the value shown is the average PM value between 9-10:00 am from all sensors within one administrative district." (B) To calculate the hourly average from the twelve 5-minute average values, the highest and the lowest value is cut off by default. "In addition, we also have safety nets, e.g. measurements of more than 250 micrograms of PM are impossible and measurements of less than 1 microgram are also impossible." (B) Such non-plausible values would be left out. In this manner, the PM values are calculated for all administrative districts in Stuttgart and its surroundings, one sees on the map.

The described way of processing and communicating the sensor data might be problematic since the hyperlocality of sensor data [9], especially PM sensor data, is an important feature that must be considered when communicating these data. A single sensor can, on the one hand, be strongly influenced by construction sites, people smoking, car emissions, or other highly local PM causing activities. On the other hand, greenery, woods, or sensors placed in yards can show low PM values. The decision to aggregate these values according to administrative districts without indicating their precise position can lead to misleading values that under- or overestimate the PM values.

In contrast, the Luftdaten map carries out no further data cleaning steps in terms of cutting off outliers or calculating hourly averages. At a large scale, hexagon figures present the median PM value of all sensors located below this hexagon, a list of all sensors merged into this hexagon makes this calculation transparent. At a very small scale, single sensors are displayed as single hexagons. In this way, the data can be visually traced back to its sourcing location and the hyperlocality of the PM data is respected.

5.5 Using Civic IoT Sensor Data for Sustainable Cities or Communities

While studying seemingly objective data, interdependencies of the data creation process need to be kept in mind. Data do not exist naturally, it is human-beings who define units of data, their scales, classifications, and meanings [19]. Especially socially created data, seems to be gathered and labelled rather subjectively and for a specific purpose [12]. In the case of environmental monitoring,

Figure 3: Screenshots from Luftdaten map and StZ Feinstaub radar map taken on Jan 2, 2020. All images are based on the same input data. Black dashed boxes marks corresponding image in the other map. Left side: Screenshots from StZ radar showing district-wise PM data aggregated to average values of the last hour. Right side: Screenshots from Luftdaten map updated every 5 min showing aggregated sensor data (upper right) and individual sensor data (lower right). Comparing hyperlocal sensor data from Luftdaten map (lower right) to maximum zoom screenshot of Stuttgart city center of StZ radar (lower left) shows how the district-wise data visualization implies a non-existent complete data coverage.

Garbys [10] describes an interdependence between environmental data, governance, citizenship, and power. In a smart sustainable city, environmental data and smart urban citizenship would be made efficient and streamlined in form of code to enhance present economic processes, rather than evolve urban democratic and ecological engagement [10]. But such supposition is challenged by the bottom-up Luftdaten.info project, which is not profit- but knowledge-oriented.

Nevertheless, the data map comparison shows that differences in the data communication may be due to the different audiences of the map services and/or the differing politics of the service providers.

The insights from the interviews and the data map comparison imply that both data maps pursue different goals of a sustainable city or community. Luftdaten.info works on an individual level - people learn how to measure PM and how to interpret the values

outside of their homes. Whereas the StZ radar together with the district-related articles has rather a general, informing function for the public in Stuttgart. Both approaches have the potential to make cities and communities more sustainable.

The Luftdaten map cherishes the hyperlocal characteristic of the PM values. Community members can optimize their ventilation behavior or avoid doing activities outside when their hyperlocal PM values are high. Smart home applications that automatically control the ventilation of a house could be coupled to PM sensors. "The best example is an elderly lady who told me she just wants to know when she can hang out her laundry." (A) These everyday applications of sensor data rely on the hyperlocal accuracy of the data rather than an average value for a district. The personal environmental monitoring and behavioral changes might create a larger awareness for emission-intensive activities in general. Nevertheless, such behavioral changes are based on individual engagements and a commitment of time and effort to install a sensor and collect the data. Hence, it is a rather small group of people who might live in a more sustainable way due to their engagement in the Luftdaten project.

The StZ Feinstaubradar in contrast functions rather like a information service for a larger public. It communicates PM values like weather information: "For example, if you look at the weather forecast for Berlin, you will see only two or three symbols for the entire city. There may be a sun in the middle, but it may still be cloudy at times in an adjacent area. We just work with a certain simplification." (B) StZ radar focuses on communicating PM concentrations to people who have not yet been much exposed to the PM topic.

Doing so, they are not respecting the hyperlocality of the sensor data. Taking another look at Figure 3 in the upper right image, one could argue that the zoomed-out Luftdaten map could already provide a "weather-like" information on the PM concentration, and one can ask why the StZ created its own map service. The reason might be that the Luftdaten.info website is probably less known in Stuttgart than the local newspaper website. It also lacks the geographical reduction to the city where residents share a common identity. In the Luftdaten map, users can navigate freely and the hexagonal units are not split by administrative borders or any other areas of social identification. Socialization and identification are classical media functions that are provided by local news media such as the StZ. In this way, people who live e.g. in the Stuttgart district "Nord" might become suddenly more aware of the PM topic and the related sustainability issues when they recognize that the PM value in their district is better or worse compared to other districts. Nevertheless, interview data showed that categorizing areas of identification in a simplified way can also lead to misunderstandings and complaints, and the data even might not be free of manipulation.

In this way, the StZ radar provides an information service on air quality which is probably less useful for individual people but might raise awareness for PM issues to a broad audience of readership. The users of the StZ radar are probably much more passive than the community around the Luftdaten project. Still, they can be confronted with the PM data in Stuttgart without directly searching for it, e.g. while reading local news on the StZ page and stumbling over a link to the PM radar. At the same time, StZ links to where the original data comes from. So people who might become attracted

to the topic are not prevented from getting more involved with Luftdaten.info.

Simultaneously, the StZ radar is used for automated journalism techniques and hence creates more output on the PM topic in the local media: "There are drop-down menus that you can see under the map. If you read through them, you will see that these texts are written in respect to the administrative area. For the area of Stuttgart you can see here the 23 city districts and you can select the areas in order to get automatically the status of fine dust." (B)

In sum, the collection of Civic IoT Sensor Data provides a more educated way of dealing with the PM topic. It could represent potential evidence for future regulations, since it may have more empirical value within a public discourse on sustainability than traditional media coverage based on opinions, interests, and/or emotions. Further, people engage themselves in the data collection and learn about the complexity of the PM field and experience open questions of scientific nature by themselves. This transparency and citizen-inclusive approach might prevent over-simplified solutions, and at the same time, it can create a basis of acceptance for regulation. Another aspect is the communication of the collected data. This case shows that a collaboration with media helps to increase visibility. If the sensor data is openly available, not only Civic IoT projects themselves can distribute data-based knowledge. News media can use them to make the insights available for a broader audience. Additionally, new formats of data journalism and automated journalism can be leveraged to communicate IoT sensor data.

Coming back to the thoughts of [11], [18] and [23], this study shows that IoT devices in form of small self-made sensor kits can have a minimum of embodied energy costs while having a large output, i.e. a worldwide locally-based community working on the measurement of PM and creating local implications on the public sphere and potential impacts on governance towards a more sustainable future. Nevertheless, one has to ask about the specific goal of such an Civic IoT project, and if the continuous data streams could be stopped once the goal is achieved. From a LIMITS perspective, the goal of Luftdaten.info could be to achieve long-term compliance to PM limitations of a region, which then would entitle the deactivation of all installed sensors in this area.

6 CONCLUSION AND OUTLOOK

The PM topic in Stuttgart can be understood as a discursive long-term process to raise awareness and change behaviors of people. This case study shows that the Civic IoT project Luftdaten.info, though being organized within limits, can contribute in multiple ways to more sustainable cities or communities:

(1) People become aware and engaged for their local environment, i.e. the low-budget and community-supported PM sensor kit offered by Luftdaten.info allows people to get active easily, and leads to behavioral changes when PM values are measured to be high or low.

(2) Managing their project in a sustainable way, i.e. Luftdaten.info takes measures to minimize their resource consumption and emissions, maximize the output, openness, and diversity of their community, and aims at a neutral and durable project funding; hence, they act exemplary and responsibly.

(3) Influencing the local public sphere, i.e. the local news medium Stuttgarter Zeitung (StZ) integrated the openly accessible PM data into an own data map StZ radar and links to the Luftdaten.info data source. This service widely enlarges the visibility of the PM data collected by Luftdaten.info and of the PM issue itself to the broader public of an established local newspaper.

Nevertheless, the data map comparison of the Luftdaten map and the StZ radar reveals how seemingly minor decisions on data analysis and visualization can lead to possibly misleading communication of the data-based knowledge.

Future research should survey community members of Luftdaten.info and readers of StZ to receive first hand information on how exactly the availability of Stuttgart PM data makes a difference to people's understandings or behaviors.

All in all, this case study suggests that interplay of Civic IoT-based engagement, locally established media, and local governance seems to be a promising way to realize sustainable cities or communities within limits. The Citizen Science approach ensures that the project is inclusive and scientifically oriented.

Referring back to Meadows claims, the project's ecological efforts link to claim (a) *"efficient, closed-loop materials systems"*. The use of widespread sensor technology for environmental monitoring does not pose a great ecological issue when concrete measures are implemented to balance the embodied energy costs of the devices (i.e. recycling, re-use, reduce shipping emissions, etc.) or to motivate behavioral changes. Regarding the other claims (b) *flexibility, innovation, and intellectual challenge*, (c) *decentralization of economic power, political influence, and scientific expertise*, (d) *media that reflect the world's diversity and at the same time unite cultures with information*, Figure 2 shows how Civic IoT projects can be a solution. Luftdaten.info, being a flexible and innovation-driven project aiming at knowledge enlargement, acts independent from political parties and economic players. Nevertheless, the publicly available PM data might have the potential to influence political decision-making via news media working with the data. In future, potentially receiving a desired public mandate, such impact might be even greater.

The results of this study emphasize Meadows' idea that *"[a]ll people and institutions play their role within the large system structure"* [16]. But as Luftdaten.info shows, it is not only *"industries, governments, environmentalists, and most especially economists [playing] essential roles in contributing to sustainability"* [16], it can also be ordinary, tech-savvy people making the first essential steps.

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