A Big Data Platform for Smart and Sustainable Cities: Environmental Monitoring Case Studies in Europe

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Abstract. One of the most challenging aspects of the actual smart city trend is to keep under control the environmental parameters with the aim of general sustainability. The impact of daily activities of humans in the city is presently very evident. The geographical and social characteristics of the cities may react and facilitate the sustainability as well as may really influence how the city may be more or less resilient to certain pollution production. After investigating the theoretical concept of Smart Sustainable City (SSC), this paper reported the work performed in supporting the aforementioned trend and analysis in three European cities (Florence, Helsinki and Cagliari) that despite having different characteristics for population and density, have some similarities, such as geomorphic aspects. In addition, two of them present a relevant port (Helsinki and Cagliari), two of them have similar urban complexity, such as traffic (Florence and Helsinki). The work presented has exploited Snap4City big data for smart city infrastructure and has been developed in the context of Snap4City, Trafair, and GHOST projects. The results have shown that critical aspects have been identified over time for pollution issues, in particular with PM10 and NOX.

Keywords: Smart Sustainable Cities · City dashboard · Snap4city · Big data · IoT · IoE · Florence · Helsinki · Cagliari

1 Introduction

Over the years, the "smart city" label has begun to no longer be considered sufficient to encompass all the possible implications related to the new idea of the city [1, 2]. On the one hand, scientific studies introduced the concept of "smart and sustainable cities" [3] so as not to lose the connotation of sustainability in the broader terminology of smart cities even when not explicitly referred to, and on the other hand, literature divided the

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smart city paradigm into eras: "smart city 1.0", "smart city 2.0" [4, 5] and, only recently, scholarships started to perceive the "smart city 3.0" [6].

The smart sustainable city that belongs to the "smart city 3.0" era is, therefore, an innovative and human-centred city that tries to achieve the fusion of two urban development strategies with a greater respect for the environment: on the one hand, the achievement of sustainability "with respect to environment, operations, functions, services, designs, and policies" [7, p. 11]; on the other hand, the pursuit of smartness with the potential of ICT in order to provide the technological infrastructures, solutions, and approaches needed for improving the quality of life, with big data analytics and context-aware computing and in light of the goals of sustainable development [8–10, p. 11–13].

As a consequence of these premises, the development of a city, or of a highly urbanized region, today more than ever, must go hand in hand with the improvement of technologies for the acquisition, management, analysis and display of information. These technologies allow real-time and constant monitoring of all urban areas in which human activities take place, by implying a smart governance of the considered context [11]. If the extended urban system is considered as a complex organic system that behaves like an articulated sentient organism, it is possible to identify some crucial hubs for its correct functioning that concern the sources (internal and external to the system), the acquisition systems, information processing and response management processes [12]. In this regard, this article reports three examples in Europe, in particular three cities at different levels of maturity of the identification and smartification process (Florence, Helsinki and Cagliari) where this process is launched through the big data platform Snap4City. To this end, the authors begin with a theoretical framework on what is meant by smart sustainable cities of the future. Subsequently, the article focuses on the data aggregation phase which includes the monitoring of environmental variables, in order to identify problems and possible operational solutions for the optimal government of the cities under study. In fact, today environmental issues appear even more of fundamental importance as they reflect wider implications not only for long-term approaches and strategies to public health, but also for a smart management and for a smart city governance, in order to better shape together the smart sustainable cities of the future.

2 The Future of Smart Sustainable Cities Considering the "Deep Ecology" Paradigm, IoT, and Big Data

Modern cities have a significant role in strategic sustainable development, in fact, according to estimates, the intense urbanization of the last few years will led about two thirds of the world's population to live in urban areas in 2050 [13], with imaginable repercussions on social and spatial issues ranging from land use modification to the management of natural resources, waste and pollution, without neglecting the effects still not determinable on climate change. These issues are clearly reflected in the Sustainable Development Goals (SGDs) of the United Nations' 2030 Agenda for Sustainable Development, which entails, among other things, making cities more sustainable, resilient, and safe (UN, 2015) [14].

Currently, therefore, all those involved in the monitoring and management of cities in a smart and sustainable way and considering the "smart city 3.0" era must face problems inherent in transforming them into sustainable cities and in this effort, fortunately, the growing availability of technologies, tools and data offers a high potential for solutions to many of the challenges in a direction that respects the environment and living beings. In relation to environmental data, their analysis allows to read the city to its ecological component, closely connected to the people and the different subsystems of the city [15, 16].

The intent of the paper is in particular, to focus on smart environment management through the so-called "deep ecology" which, according to Vinod Kumar [15] considers, through basic principles, the environment, not exclusively that one of "living plants and animals, or the paradigmatic thought of the word "environment", but basically the world around us, the place in which we live" [15, p. 10]. In relation to environmental data under the "deep ecology" paradigm, their analysis allows to read the city to its ecological component, closely connected to the people and the different subsystems of the city. In addition, the data availability alone is not a sufficient condition for the provision of smart services. It is necessary to adopt an ontology-based approach, namely an approach based on the formal and explicit specification of a conceptualization, which allows the representation and semantic interoperability of geospatial data and related processes. This is because "the lack of explicit semantics inhibits the dynamic selection of those geoprocessing data, services and workflows needed for processing geospatial information and discovering knowledge in a data-rich distributed environment" [17, p. 37]. The integration of semantic information makes location-based services smart and truly capable of improving a smart city. The amount of information available today is such that the problems related to the quality and meaning of it must already be addressed in the design of an architecture to support the smart city. Namely, first of all, the reference scenarios must be well defined to analyse the specific needs of citizens and analyse their behaviour and the actions that contribute to reaching them. Within these scenarios, georeferenced information is crucial for obtaining a context-sensitive description and an analysis of emerging local practices.

Furthermore, considering the georeferred or in any case positional nature of the sensor measurements, it is important to consider the area dependence of the measurements, even if in the case of big data [18], the large size of the dataset allows to limit the problems of the area nature by treating the choices of aggregation of data at different territorial levels to check for critical issues.

The analysis of big data amplifies the interpretative capacities of cities as sentient organisms with new meanings and, since it is the prerequisite for the creation of more in-depth knowledge bases, it facilitates the adoption of targeted and smart solutions, also in relation to environmental problems, traffic, health and their interconnections [11, 12]. In this new flow, sensors act as inputs for big data applications, together with all the information of geospatial, political and social context. The combination of IoT and analytics through big data is rapidly changing the way cities themselves operate and the dynamics through which they can be monitored and managed also regarding decision-making processes in the various sectors of urban planning, in accordance with the principles of social, economic and environmental sustainability. An example is given by the optimization of energy distribution, with monitoring of consumption or

interruption peaks, or by the management of mobility, by monitoring traffic in real time or by mitigating environmental risks. In concrete terms, in a context of smart and sustainable cities, the analysis of big data involves the implementation of very sophisticated software applications and databases managed by machines with very high computing power, such as to transform raw data flows into knowledge useful for urban planning and design.

Technologies are nowadays so invasive that they permeate objects, structures, infrastructures, ecosystems and living beings, so much so that expressions such as the Internet of Things (IoT) [19] or the Internet of Everything (IoE). They are referring to a physical environment on which an Internet infrastructure support data collection device, including RFID, NFC, GPS, infrared sensors, laser scanner, etc. Taking advantage of this expansion of global connectivity, the growth in data traffic, which was already quadruple between 2011 and 2016, shows no sign of decreasing [20], thanks also to the production of sensors low cost and the enhancement of wireless communication networks and Web technologies.

It can therefore be easily understood that the IoT, in an approach oriented to constant monitoring to improve air quality, can represent a decisive component for urban development within the ICT infrastructure of sustainable smart cities, due to its great potential to promote environmental sustainability.

Empirical examples of what is described in this paragraph will be shown in the next paragraph through the description of the three case studies.

3 Empirical Examples of IoT and IoE in the Case Studies of Florence, Helsinki and Cagliari

The integration among physical (material) and digital (immaterial) entities is increasingly widespread, namely the data describing a smart and sustainable city come from different sources and providers, that usually are available under different standards and communication protocols, realized with distinct technologies of IoT Devices.

Moreover, they are related to all the variety of areas describing a city. Thus, they describe transport and traffic systems, mobility of goods and people, land use and land cover, environmental factors, resources and energy consumption, waste, home automation and building automation, etc. This scenario from one hand, has made possible the birth of a whole new class of applications and services, from the other the use of Big Data analysis is necessary to manage a so huge variety of dataset. The use of Big Data platforms, applied in such context and having a mature experimentation level, can be considered a key factor in promoting environmental sustainability.

In this regard, the authors describe three empirical case studies: Florence, Helsinki and Cagliari. In these cities the Snap4city Big Data Platform, has been applied. The Snap4City methodology starts with the work related to the analysis of the context and the study of the goals to be reached to make the city smart and sustainable, enabling Living Lab Support and co-working. This analysis is finalized to determine which are the main relevant aspects they continuously want to monitor basing and the available

resources. The next step involves the analysis of the available data coming from the different city providers that operate and collaborate with the municipalities to provide them public or private services. Then the datasets must be ingested in the Big Data Platform, according to the objectives outlined in the first phase. Only after an efficient data gathering and data aggregation activity, it is possible to proceed with data analytic processes for the production of smart services. For example, by means of computing predictions, anomaly detection, Key Performance Indicators (KPI) monitoring, heat-maps interpolation, and studying a large set of derived data: trajectories, hot Point of Interest, origin and destination matrices, etc. The final phase, no less important, involves the exploitation of the results obtained through the creation of ad hoc visualization tools, such as mobile applications for citizens and dashboards for decision makers. These highly complex tools can also work as actuators and are able to manage any type of event from the most classic maps enriched with the Points of Interest, through comparative graphs for the management of heatmaps that are updated in real time.

In the City of Florence were made the first experiments in various contexts related to many different areas of interest such as Mobility, Environment and Pollution, Industry 4.0, Energy, Social Media, Emergency Management, Healthiness.

The City of Helsinki realized an experimentation based on the Snap4City platform, in the following domains: environment, citizen awareness, dashboard, mobile app for a number of different categories of users: citizens, tourists, and city officers. The city of Cagliari has experimented the Snap4city platform mainly to take advantages and monitor the aspects connected to the fields of tourism, culture and mobility, as appears in Fig. 1, in which a search on the TPL (Local Public Transport) timetables around a point is visible.

The comparative analysis among the three cities is realized in this paper on the environmental aspects. The study of pollution levels in urban areas, is one of the most strategic topics when it is talked about a smart and sustainable city under the “smart city 3.0” era, because it is strictly connected with the health of the city, allowing long-term approaches and strategies also in managing and designing their future. In addition, cities have an interest in understanding how much pollution affects the quality of the air that citizens breath in order to properly regulate urban mobility and give to all the awareness that they are living in a city that is increasingly technological and oriented towards focusing on citizens’ health and thus quality of life. The air quality in a city is primarily related to the production of pollution coming from the vehicles running in the city [21].

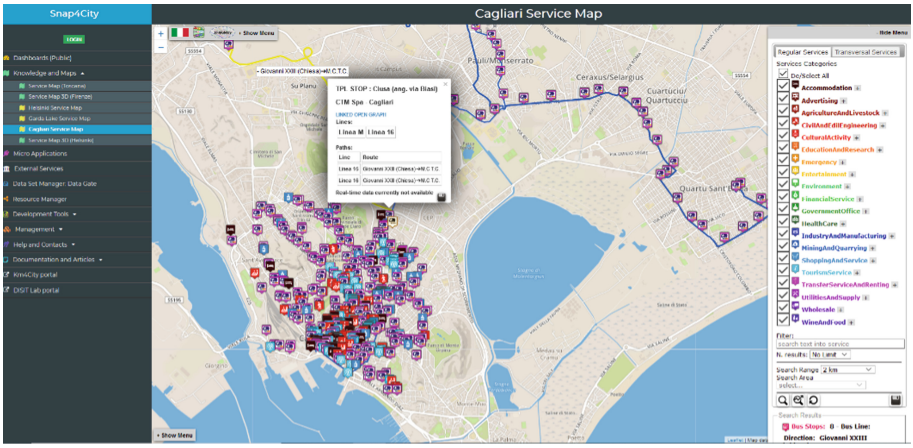

Fig. 1. Public Transport Lines in Cagliari: routes, stops, timetables around a point with a radius of 2 km

The three cities, as can be seen in Table 1, are different both demographically and territorially.

Table 1. Inhabitants, surface and density of the 3 cities under study

City	Inhabitants	Surface (km^2)	Density (inhab./km^2)
Helsinki	648.650	213,8	3.033,91
Florence	378.917	102,41	3.700
Cagliari	154.227	85,01	1.814,22

4 The Big Data Platform Snap4City for the Case Studies

Each city is faced with its own specific problems, due to its geographical location, geomorphology or its history and culture that make it unique. Although digital and technology-based approaches are often considered in the literature as a universal solution. When replicating a model in different cities or geographical areas, it is necessary to take into account individual specificities and therefore develop strategies that can draw inspiration from other contexts but are as unique and specific as the city itself [22].

Demonstrating how the fabric of smart and sustainable cities is somehow interwoven with electronic fibers, sewn together with integrated real-time detection and measurement devices, communication networks and advanced information processing systems, we bring here Snap4City, as a scalable *Smart aNalytic APplication builder for sentient Cities* [23].

Snap4city has been created to provide many online tools and guidelines to involve all different kinds of organizations (e.g., Research Centres and Universities, small

business, large industries, public administrations and local governments) and citizens (e.g., city operators, resource operators, companies, tech providers, category Associations, corporations, research groups, advertisers, city users, community builders). Snap4city is GDPR (General Data Protection Regulation of the European Commission) compliant, it ingests and manages large set of datasets and provides a set of smart city APIs to access the data that can be publicly available or private (the Application Program Interface, APIs in this case are available only for the people having the permission on the data - e.g., using the registration to the platform, [24, 25]).

The Snap4City Big Data Architecture has been created to as a smart city infrastructure and it is actually applied in many Italian (Firenze, Cagliari, Pisa, Livorno, Prato, Lonato, etc.) and European cities (Helsinki, Antwerp, Santiago De Compostela) and their surrounding geographical area (such as in Italy the region of Tuscany, Sardinia and Lombardia but also Belgium and Finland) [11].

The Snap4City solution provides methods and tools to quickly create a wide range of smart city applications by leveraging heterogeneous data. It enables services for stakeholders through IoT/IoE, provides Big Data analytics and technologies, provides Smart Living Labs for enabling in co-working activities all the different people involved in a Sentient city (city decision-makers, researchers, stakeholders, citizens).

Moreover, it is capable to show in advanced Dashboards information, services, applications and dashboards sharing environments for differentiated users and developers, urban operators and decision makers, serving the city [26, 27].

As anticipated, the reference scenario for comparing the three cities Florence, Helsinki and Cagliari relates to the real-time analysis of the major polluting factors in the context of a Smart City and the estimation of pollution levels for the next 48 h, exploiting the potential of the Snap4City platform (Table 2). There main work phases that must be addressed to reach the final goal are: i) Data analysis; ii) Data ingestion; iii) Data analytic and development/application/comparison of predicting algorithms and related Visualization.

Phase I – Data analysis. In Table 1 the details related to the available raw data for each city. The data considered are related to pollution, weather and weather predictions and comes from different providers. All the data founded are Open Data, excluding those on pollution in Helsinki, coming from Forum Virium activities and in which we have a specific agreement in the context of Snap4City, Select4City PCP of the European Commission. All the data is ingested in a periodical modality, each data with the frequency reported in the table, excluding those related to Cagliari. The Ingestion phase in the City of Cagliari is under development. Moreover, we pose a (*) when data is provided both in a dynamic modality for every day and as a prediction.

Phase II – Data ingestion. In this phase a set of data gathering processes are created (one for each dataset), that can be IoT Applications, based on NodeRED or ETL (Extract Transform and Load) processes based on Spoon, [16, 18, 20]. The static data (sensor position, city, type of data, unit measures, frequency of update, etc.) are semantically aggregated, in compliance with the KM4City multi-domains ontology [33] and the dynamic data are automatically updated thanks to the fact that each IoT App or ETL runs basing on the frequency update of the related dataset, as reported in the above table.

Table 2. Data analysis among Florence, Helsinki, Cagliari.

City	Data category	Provider	Frequency of update	Type of pollutants	# of sensors
Florence	Pollution	Arpat [28] validated data (from experts)	daily (related to the previous day)	NO2, CO, H2S, C6H6, O3	6
	Pollution	Arpat instrumental data (non-validated)	hourly	NO2, CO, H2S, C6H6, O3	6
	Pollution	CNR C calibrated data	5 min	CO, CO2, NO, O3, PM10, PM2.5,	10
	Weather	CNR	5 min	Humidity, temperature	10
	Weather	OpenWeather [29]	hourly and prediction (*) for next 3 days	humidity*, temperature*, pressure*, wind speed and direction*, rain, temp_max*, temp_min*, snow, clouds*, weather description (e.g. clear sky), seaLevel Pressure*, sunrise and sunset, ground level pressure*	2
Helsinki	Pollution	Finnish meteorological Institute - ENFUSER [30]	hourly	NO, NO2, SO2, PM10, PM2.5, O3, AQI,	5
	Pollution	Forum Virium project, giving sensors to citizens	5 min	NO, NO2, SO2, O3, PM10, PM2.5	20
	Pollution predictions	ENFUSER	For the next 24 h (prediction for every hour)	NO2, O3, AQI [31], PM10, PM2.5	30 heatmaps
	Weather	OpenWeather [29]	hourly and prediction for next 3 days	Same as Florence	3
Cagliari	Pollution	SardegnaAmbiente [32] validated data (experts)	Daily (related to the previous day)	CO, NO2, SO2, O3, PM10, PM2.5, C6H6	8
	Pollution	SardegnaAmbiente instrumental data (non-validated)	hourly	CO, NO2, SO2, O3, PM10, PM2.5, C6H6	8
	Weather	OpenWeather [29]	hourly and prediction for next 3 days	Same as Florence	8

Phase III – Data analytic and development/application/comparison of predicting algorithms. In order to have a complete picture of the pollution situation in a smart city, it is necessary to start from the air quality data analyzing the level of the several pollution aspects have to be assessed measuring, for example: SO2, NO, NO2, O3, CO, CO2, PM10, PM2.5, etc., but also considering the weather conditions and weather forecasts, and traffic data. This makes it possible to monitor pollution in two different levels: to have the current state but also to elaborate, thanks to the use of predictive methods, the future state of pollutant levels.

Florence:

- Algorithms to estimate heatmaps for each pollutant. The frequency in which the interpolation is estimated depends on the data frequency, thus the algorithms run every hour on PM10, PM2.5, NO2, CO, humidity, air temperature.
- Algorithms to obtain the European Air Quality Index, EAQI, based on the European Environment Agency guidelines [34]. The EAQI takes into account for air quality assessment about PM10, PM2.5, NO2, O3, and SO2 considering the worst cases among the values of those measures according to a formula. The resulting index from 1 to 5 (good, fair, moderate, poor and very poor) indicate the quality of air.

Helsinki:

- Algorithms to estimate heatmaps for each pollutant. The frequency in which the interpolation is estimated depends on the data frequency, thus the algorithms run every hour on PM10, PM2.5, NO2, AQI, humidity, air temperature.
- Algorithms to obtain the European Air Quality Index, EAQI, based on the European Environment Agency guidelines, as described for the city of Florence.
- Visualization of the ENFUSER Open Data AQI heatmaps. The Finnish Air Quality Index is a hourly index which describes the air quality today, based on hourly values and updated every hour. The index takes into account the concentrations of sulphur dioxide (SO_2), nitrogen dioxide (NO_2), respirable particles (PM_{10}), fine particles ($PM_{2.5}$), ozone (O_3) carbon monoxide (CO), and the Total Reduced Sulphur compounds (TRS). The air quality index in use in Finland is developed and maintained by the Helsinki Region Environmental Services Authority HSY and the National Institute for Health and Welfare THL.
- Visualization of the ENFUSER Open Data heatmap: hourly previsions for the next 24 h on AQI, PM10, PM2.5 on NO2, O3, AQI, PM10, PM2.5.

Heatmaps are computed using a bilinear interpolation (Akima method, [40, 41]). Interpolated maps are delimited by external sensors and the value are estimated inside the external sensors area (triangulation). The bivariate interpolation method consists of five procedures: (1) triangulation (i.e., partitioning into a number of triangles) of the x-y plane; (2) selection of several data points that are closest to each data point (sensor) and are used for estimating the partial derivatives; (3) organization of the output with respect to triangle numbers; (4) estimation of partial derivatives at each data point; and (5) punctual interpolation at each output point. The z value of the function at point of coordinates (x, y) in a triangle is interpolated by a bivariate fifth-degree polynomial in x and y. The algorithm has been implemented as an R script, that is put in execution periodically on the Snap4City Infrastructure.

In Fig. 2, the hourly heatmaps related to the cities of Helsinki and Florence are compared. Moreover, a set of heatmap controls is available and useful to go back and forth in time as method to compare the status of pollutants and weather data not only today but also in the past (and in future in case of the ENFUSER data). While in Fig. 3, is available the comparison, which once again connects the cities of Helsinki and Florence. This model makes predictions on the next 48 h at two level (3 and 6 m) on NOx, also in this case the heatmap controls allow the user to scroll through time and display heatmaps both in past and future. It as possible to view a video showing the next 24 h. Looking at Fig. 3, the NO2 heatmaps are shown.

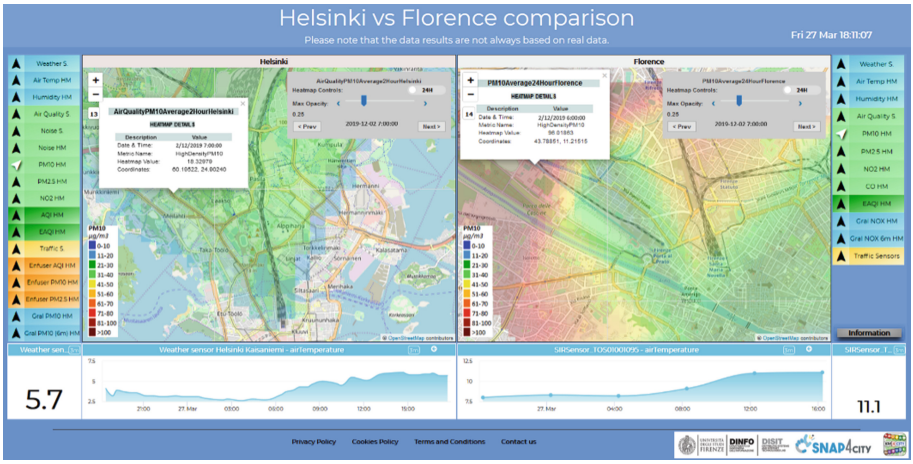

Fig. 2. Snap4City Dashboard comparing Helsinki and Florence: PM10 heatmaps [35].

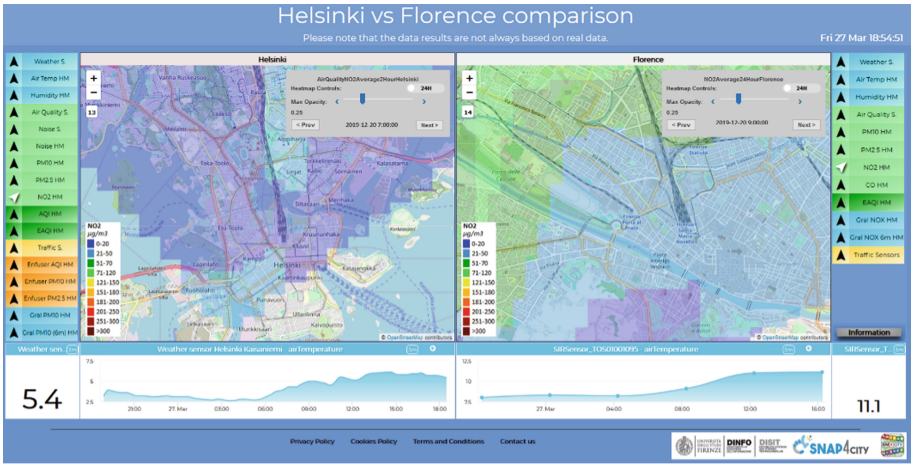

Fig. 3. Snap4City. Prediction of NO2 presence on Helsinki and Florence.

In order to make a comparison on the three different European, for each city two sensors have been selected (from the Air quality monitoring stations) covering a downtown position and a peripherical position. In Table 3, for each sensor are reported the Annual Means related to PM10, PM2.5, NOX, EAQI. NOx is a generic term for the nitrogen oxides that are most relevant for air pollution, produced from combustion, namely nitric oxide (NO) and nitrogen dioxide (NO2). For the city of Cagliari on the NO2, is available. Moreover, only for the city of Cagliari, the data are not already ingested in the Snap4City Platform and comes directly from the provider (SardegnaAmbiente) and are related to 2018. The other means comes from data on Snap4City.

Table 3 Comparison among Florence, Helsinki, Cagliari on Annual Means related to PM2.5, PM10, NOX, AQI/EAQI, considering that regarding Cagliari, for EAQI (*) only a qualitative evaluation is available in the Sardegna Ambiente Portal.

Sensor name	Mean annual PM10	Mean annual PM2.5	Mean annual NOX	Mean annual EAQI
Florence Gramsci – downtown	27.52	15.59	97.03	2.43 (Moderate)
Florence Airport - periphery	21.07	21.89	64.59	2.67 (Moderate)
Helsinki station - downtown	19.34	6.83	21.62	1.64 (Fair)
Helsinki Länsisatama 4 in Jätkäsaari periphery	no measures	4.62	15.21	1.73 (Fair)
Cagliari Cenca1 - Periphery	30.16	18.68	28.51 (NO2)	Fair (*)
Cagliari Cenmo1 - downtown	27.63	11.48	13.44 (NO2)	Fair (*)

5 Discussions and Conclusions

Smart and sustainable cities of the future represent a techno-urban innovation that triggered transformative processes that are developed due to the growing infiltration of sensors and of the enhancement of connectivity in urban systems with the consequent production of data, services, functions and projects [36, 37].

As with any transformation process in sustainable smart cities, it is necessary to establish road maps that take into account virtuous experiences and are able to make continuous improvements in urban contexts where they operate, always starting from the verification of the starting conditions, that is, having awareness the degree of maturity and the city's willingness to change.

The integration of IoT and big data will undoubtedly have significant short- and long-term effects in the creation of increasingly smart sustainable cities, even if open challenges for the analysis and management of big data must not be overlooked,

including all the related implications. to ownership and privacy, to the integration of databases between different urban domains, data sharing, in addition to the usual long-standing questions regarding uncertainty, incompleteness, accuracy and quality of data.

This paper reported the work performed in supporting this trend and analysis in three cities in Europe, which are from certain point of views are similar: Florence, Helsinki and Cagliari, for geomorphic aspects and for population. Two of them present a relevant port, two of them have similar population and traffic, etc. The results have shown that critical aspects have been identified for PM10 and NOX over time.

The Snap4city architecture, quickly described in this paper, through experimentation conducted in different urban areas, highlights a paradigm shift, since it does not adopt an approach simply driven by technology but more specifically driven by data. Big data, open data, sensors, IoT, IoE for monitoring, controlling and managing urban developments, resources, urban infrastructure, energy consumption, traffic congestion, waste, pollution, risks and people, are the tools for governance and urban planning, for which the expected changes are a consequence of a decision-making process based on the data [38, 39]. The work presented has exploited Snap4City bigdata for smart city infrastructure and has been developed in the context of Snap4City, TRAFAIR, and GHOST projects.

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18. The term big data means the availability and proliferation of large quantities of data characterized by heterogeneity, complexity, temporality, modifiability and their use in disparate application domains. By convention and for brevity it is usual to refer to the well-known 5 V, that is velocity, volume, value, variety, and veracity. (to which later validity and volatility were added). Due to these characteristics, the computational and analytical capabilities of standard software applications and conventional database infrastructures are no longer sufficient for the processing and management of big data. The data acquired by sensors are analyzed through data-mining and machine learning techniques in order to build descriptive and predictive models to support decisions
19. The IoT actually constitutes an increasingly sophisticated network of sensors (i.e. electronic devices that react to certain physical inputs and return a digital signal) that affects almost every type of everyday object: roads, railways, bridges, roads, buildings, water systems, electricity networks, vehicles, appliances, goods, machines, animals, plants, soil and air, including people themselves. In essence, the connectivity achieved by the IoT involves living beings, objects and places and is destined to grow

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