Environmental sensing and simulation for healthy districts: a comparison between field measurements and CFD model

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Chapter 82

Environmental Sensing and Simulation for Healthy Districts: A Comparison Between Field Measurements and CFD Model

Matteo Giovanardi, Matteo Trane, and Riccardo Pollo

Abstract Atmospheric Particulate Matter (PM) is considered among the main risk factors for cardiovascular, respiratory, and carcinogenic diseases. Besides, heat waves accounted for 68% of natural hazard-related deaths in Europe between 1980 and 2017 and many climate models project a global rise in climate hazards. Environmental Monitoring (EM) is a key resource to control health determinants, addressing threats arising from unhealthy external conditions. Forecasting models may need data coming from pervasive distributed sensor networks and computational simulations. Moreover, district-scale Environmental Sensing (ES) and Environmental Modelling Simulation (EMS) may identify criticalities and specific strategies to mitigate climate risk affecting physical health. This paper compares the output from ES, by field measurements during a "climate walk" joined by more than 60 people, with EMS, by a Computational Fluid Dynamic software (CFD). The assessment has been performed on a real urban district. For on-site measurements, data were acquired by low-cost IoT-based sensors developed by the authors. For simulations, we used ENVI-met, a prognostic non-hydrostatic CFD. Potential Air Temperature and PM 10-2.5 concentration parameters have been measured and simulated on a specific winter day. Results are presented and discussed through a visualisation matrix making the comparison direct. The analysis of the results pointed out the role of ES and EMS for high-resolution scenarios assessment. Although real-time monitoring needs extensive infrastructure at the urban scale, the use of low-cost sensors and a citizen science approach could provide precise input data to support even more accurate models, towards a healthy district site-specific design perspective. This may finally contribute to achieving the Sustainable Development Goal 11.6, aiming at reducing the adverse environmental impact of cities, thus paying particular attention to air quality.

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Keywords Environmental sensing · Environmental modelling and simulation · Healthy district · ENVI-met · IoT

82.1 Introduction

By aiming at making cities and human settlements inclusive, safe and resilient, the Sustainable Development Goal 11 points out to reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality (target 11.6). Despite some progress achieved in reducing exposure in certain countries, the global health burden of ambient fine Particulate Matter (PM) is still increasing annually (Southerland et al. 2022). Air pollution causes a wide range of adverse health effects, even at the lowest observable concentrations (Strak et al. 2021). Alongside this, heat waves accounted for 68% of natural hazard-related deaths in Europe between 1980 and 2017 and many climate models project a global rise in climate hazards (Woetzel et al. 2020). Emissions by anthropogenic sources are the main factors in the processes causing air pollution and heat waves in cities. Even though some of these processes regard planetary-scale climatic phenomena, planning at regional and local scale has to respond to imminent challenges due to global warming and threats arising for human health. For instance, the role of greenery has been largely discussed as a pollution mitigating element (Rui et al. 2019). The urban fabric can allow natural ventilation or obstruct the wind flows, influencing PM concentrations and temperature cool down.

Urban surface materials are determinant in lowering the air temperatures, thus improving comfort for people in public spaces.

Given the complexity of these multi-scale issues, Environmental Monitoring (EM) is a key resource for health determinant control. EM asks for data that may come from Environmental Sensing (ES), by a distributed pervasive sensor network monitoring several Environmental Parameters (EPs), and Environmental Modelling and Simulation (EMS), by advanced computational tools forecasting patterns based on given boundary conditions and site-specific features. This research combines both approaches, supported by a Citizen-Science (CS) experience, for EM purposes. The second section of this paper describes the Materials and Methods applied and introduces the case study.

The third section illustrates the Results obtained both from the on-field measurement and a Computational Fluid Dynamics (CFD) simulation, while the fourth one discusses them by a visualisation matrix. Finally, the Conclusions present the advantages coming from the combination of ES and EMS for scenarios assessment, towards a healthy district site-specific design perspective.

82.2 Materials and Methods

The research was carried out in Turin, a city in north-western Italy, surrounded by the western Alpine (Cfa climate according to Köppen–Geiger classification). The case study is within Regio Parco district (45°04′ N 7°42′ E), a peripheral area in the north-eastern part of the city, located near the Po River and some main green infrastructures.

The area of analysis extends for approximately 640,000 m^2 (800 m × 800 m).

82.2.1 A Citizen-Science Experience for Environmental Sensing

ES can be defined as the process by which acquiring real-time data on several EPs through a distributed pervasive sensor network. ES systems can range from dynamic (mobile) to purely static deployments and can monitor different built environment parameters, to improve process efficiency, ensure optimal environmental conditions, highlight patterns, detect anomalies, or avoid stress conditions. ES allows for major knowledge on dynamic phenomena as it is enabled by an Internet of Things (IoT) virtual infrastructure, consisting of a network of interconnected objects based on standard communication protocols (Giovanardi et al. 2021).

In the context of an innovative teaching experience, 62 students were part of the on-field measurement campaign. This CS approach led us to acquire real-time data on several EPs at the same time: air temperature (AT), relative humidity (RH), PM 2.5-10 concentration, and air pressure. The on-field measurement campaign was carried out by using IoT-based devices (Fig. 82.1). Although in a prototypal status, these devices were successfully used in previous research, after its calibration and validation (Montrucchio et al. 2020). The device consists of four PM sensors using laser scattering technology, a DHT22 sensor for air temperature and relative humidity, a barometric sensor for air pressure, and real-time clock for temporal data synchronisation. It also incorporates a Raspberry Pi simple-board computer, and its micro-SD card stores data by a Python script. The external case was 3D printed and it measures 44 mm × 36 mm × 12 mm.

The low-cost device (total cost around 40 euros) is powered by portable batteries.

The campaign was organised in five different paths, namely Climate Walks (CWs) *A-B-C-D-E* (Fig. 82.2), and took place on 29 November 2021 from 1.45 to 3.45 P.M. approximately. Each CW consisted of some stop points, where students were given pre-printed surveys too, to fill in with the time of arrival at and departure from each stop (approximately 15 min per stop), data about traffic (number of cars passing by per road lane), and personal feelings about environmental quality. At the end of the walks, surveys were collected and data on road traffic was used as input to model the pollutant sources with reliable site-specific values. The paths were also recorded and geo-referenced by using the application Open GPX tracker, to match the data

Fig. 82.1 IoT-based device for monitoring air quality, temperature, humidity, and pressure

acquired from the devices with the time interval spent in each stop and the traffic data coming from surveys.

Fig. 82.2 Climate walks

82.2.2 CFD for Environmental Modelling and Simulation

For EMS purposes, we used the software ENVI-met[1] version 5.0.2, a holistic three-dimensional non-hydrostatic CFD for the simulation of surface-plant-air interactions in urban environments. The district area was modelled with a 5 × 5 × 2 m grid cell resolution (xyz), where buildings, horizontal and vertical greenery, roads and pavements, natural surfaces, and pollutant sources were digitised. As for the meteorological input data, we used the ones provided by ARPA Piedmont[2] on 29 November 2021 (Table 82.1). Data were acquired from the nearest urban meteorological station, 4 km far as the crow flies from our campaign's start meeting point (Torino Grassi station). The simulation time was set to run for 48 h. We considered the second 24 h results, which are more accurate as ENVI-met requires some spin-up time. Although doubling the simulation timing, this could turn out into more accurate results, especially in the afternoon and evening hours (Middel et al. 2014). For the purposes of this research, we mainly focused on Potential Air Temperature (PAT) (°C) and PM 2.5-10 concentration ($\mu g/m^3$). PAT and PM were evaluated at 2 m height from the soil.

As for the pollution sources modelling, in absence of detailed data, punctual emissions due to heating from buildings were not considered. However, this approximation does not invalidate the results: as reported by ARPA Piemonte (2019), the main source of PM in Turin is actually linked to the traffic (Fig. 82.3). Thus, linear traffic sources were sized by combining on-site traffic measurements, carried out during the CWs, and the Traffic Tool in the Database Manager.

Specifically, it calculates the emission profiles per linear source type by providing an equivalent hourly flow rate profile after injecting a type-day total car volume (Veh/h). Its calculations are based on standard emission rate (HBEFA 2022). PM 2.5 was calculated as a fraction of PM 10 according to Schafer et al. (2021) (36% out of PM 10 in inner roads, 53% in roads at urban fringe and suburban roads) (Fig. 82.4). For roads with no traffic measures, we used data provided by a regional report, providing traffic volumes per hour on a standard day in November (Regione Piemonte 2017). In total, we created 11 linear emission profiles (Table 82.2). The estimation of the urban bus rate over the total traffic volume was carried out by considering the number of bus lanes crossing the roads,[3] number of passages throughout the day according to specific hour intervals[4] and real-time data on bus lines.[5]

Background levels were set (6 $\mu g/m^3$ for PM 2.5, 10 $\mu g/m^3$ for PM 10) according to the lowest most recurrent values acquired by the sensors.

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[1] Developed by M. Bruse (ENVI-met GmbH, Essen, Germany).

[2] Regional Agency for the Environmental Protection: http://www.arpa.piemonte.it/.

[3] https://www.gtt.to.it/cms/risorse/urbana/mappa/mapparete.pdf.

[4] https://www.gtt.to.it/cms/risorse/urbana/intervalli_sito.pdf.

[5] https://www.gtt.to.it/cms/percorari/urbano?view=linee&bacino=U.

Table 82.1 Meteorological data on 29 November, 2021 by Torino Grassi ARPA station

Hour	Air temperature (°C)	Relative humidity (%)	Wind speed (m/s)	Wind direction (deg.)	Global radiation (W/m^2)
00:00	1.6	80	0.6	227	–
01:00	1.4	82	0.7	161	–
02:00	0.3	87	0.6	316	–
03:00	– 0.1	88	1.1	89	–
04:00	– 0.2	81	0.4	326	–
05:00	– 0.1	80	1.5	276	–
06:00	0.4	74	1.3	242	–
07:00	0.8	71	1.2	224	–
08:00	1.6	68	1	221	43
09:00	3.1	73	0.5	94	253
10:00	7.1	62	0.9	163	372
11:00	9.5	38	1.4	126	427
12:00	11	22	0.6	120	411
13:00	10.9	17	0.9	106	351
14:00	11.3	18	1.4	88	275
15:00	10.6	17	3.4	317	208
16:00	9.3	15	4.4	328	–
17:00	7.9	17	2.8	323	–
18:00	7.4	21	2.4	247	–
19:00	6.9	23	3.4	290	–
20:00	6.6	24	2.9	263	–
21:00	5.3	25	1.4	100	–
22:00	5	30	1.2	174	–
23:00	4.4	39	1.4	150	–

82.3 Results

82.3.1 Results from ES Campaign

About 120′000 PM data were collected during the CWs. Data coming from four sensors within the devices were averaged to obtain a single PM 2.5 and PM10 data, and the results refer to a time period of ~ 90 min grouped in 10-min steps. The PM 10 average data varies between 6 and 13 μg/m^3, while PM 2.5 ranges between 4 and 9 μg/m^3, accounting for about 60% of the PM 10 share. As shown in Fig. 82.5, the variance of the average data is minimal, with the exception of CW *E*. A more in-depth analysis for each walk was carried out to deepen the correlation with endogenous factors. For example, in CW *C*, a higher level of PM is recorded at the road junction

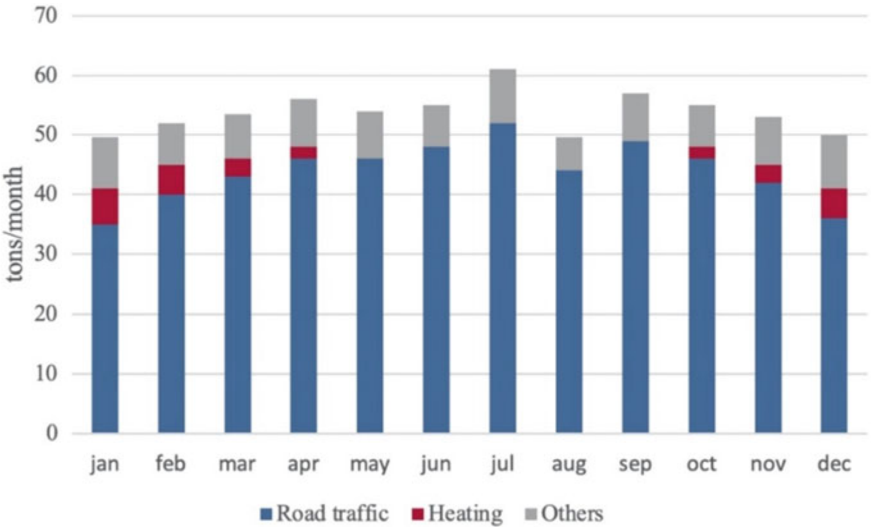

Fig. 82.3 PM 10 emission profile in Turin. Based on ARPA 2019

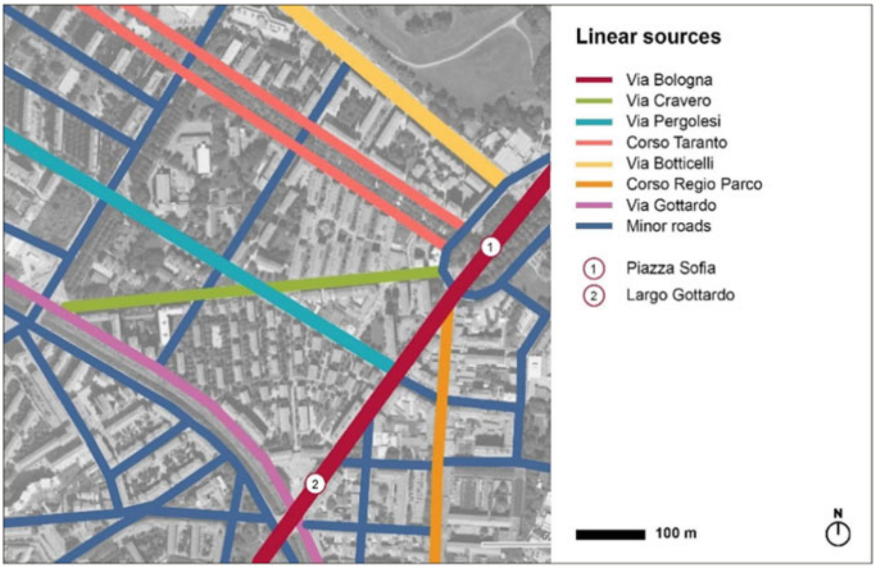

Fig. 82.4 Road linear sources

Table 82.2 Traffic volumes/road/day

Road	Road type on ENVI-met	Traffic volume (Veh/d)	Public transport (Veh/d)
1a. Via Bologna—P.zza Sofia	Road at urban fringe	23,200	620
1b. Via Bologna—L. Gottardo	Road at urban fringe	21,000	400
1c. Via Bologna	Road at urban fringe	21,000	540
2. Via Cravero	Inner road	5000	100
3. Via Pergolesi	Inner road	5000	100
4. Corso Taranto	Sub-urban road	14,000	115
5. Via Botticelli	Road at urban fringe	21,000	170
6. Corso Regio Parco	Sub-urban road	17,000	–
7. Via Gottardo	Inner road	5000	140
8a. Minor roads (1 lane)	Inner road	2100	–
8b. Minor roads (2 lanes)	Inner road	2100	–

between Via Bologna and Via Pergolesi, while in CW *E*, higher pollution levels are monitored at the intersection of via Maddalene, via Sempione, and via Bologna. The PM values were usually higher at main street intersections. As for AT and RH, the values recorded are partially higher than those officially monitored. More precisely, between 2 and 3 P.M., 11 °C (AT) and 17% (RH) was recorded by ARPA, compared to 15 °C and 20% respectively acquired by the devices on average.

82.3.2 Results from EMS

PM 2.5 and PM 10 concentration peaks were present at 7:00 A.M., while at 2:00 pm and 3:00 P.M., slightly lower values resulted from EMS compared to the ones acquired from the devices (Fig. 82.6). However, the major criticalities were present in correspondence with the main traffic sources, namely Corso Taranto, Via Botticelli, and Via Bologna. In the first, pollutants were prevented from removal by the building curtain in the north direction (considering the prevalent direction of the wind on that day), while in the second and the third, the traffic volume was much higher than in all other roads. One can still highlight how pollutants are generally lower in inner areas, where the traffic is generally lower or absent and the amount of greenery is higher.

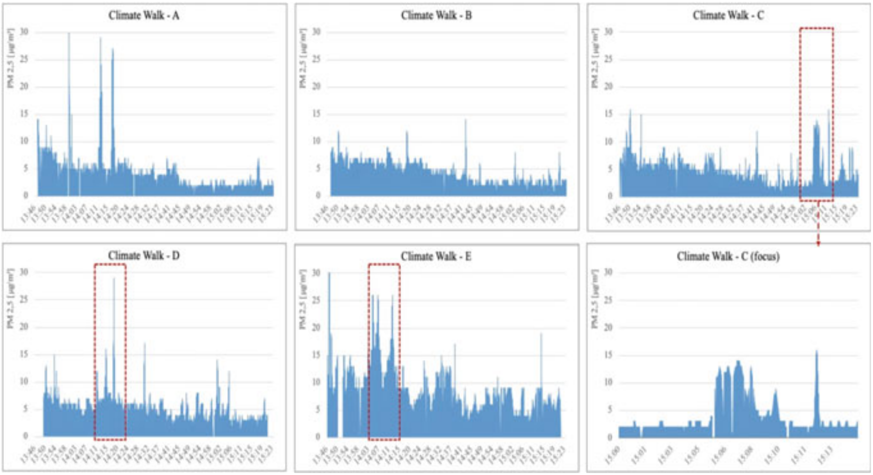

Fig. 82.5 PM2.5 values from different climate walks and a focus on path C. In the red boxes time-steps at crossroads with Via Bologna

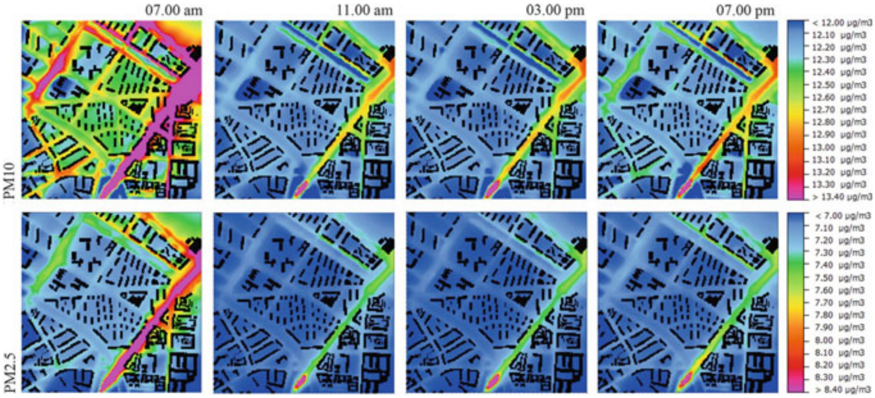

Fig. 82.6 PM10 and PM2.5 concentration at 7:00 A.M., 11:00 A.M., 3:00 P.M., and 7:00 P.M.

82.4 Discussion

Constant development in computational abilities has been allowing more advanced approaches for microclimate analysis and modelling, emphasising its high capacity of solving complex phenomena and nonlinearity of urban climate systems (Liu et al. 2020). Indeed, EMS makes it possible to analyse EPs over a relatively wide area, also predicting the microclimate conditions under different planning scenarios (Bartesaghi Koc et al. 2018). While data coming from sensors point out values that are valid for a certain path (if they are dynamic sensors, as in our case) or a single point in the space (if they are static ones), relative to a specific narrow time, EMS offers a more comprehensive overview on several EPs, describing trend and pattern throughout a type-day with a higher space resolution.

The results coming from ES and EMS are compared in a visualisation matrix including the data coming from the official meteorological urban station (Fig. 82.7).

Average PM 2.5 and 10 values by ES were very similar to the EMS outputs, although in certain areas, the values acquired by ES were slightly higher. However, in both cases, we can still assume a certain correspondence between peak values and traffic, especially at the intersections between Via Bologna and minor roads. Daily urban average values provided by the ARPA station were actually higher (28 µg/m^3 for PM 10 and 19 µg/m^3 for PM 2.5), but they do not allow for any high-resolution information and further in-depth considerations. Specifically, acquisition by the devices could be considered more accurate as they capture traffic-related

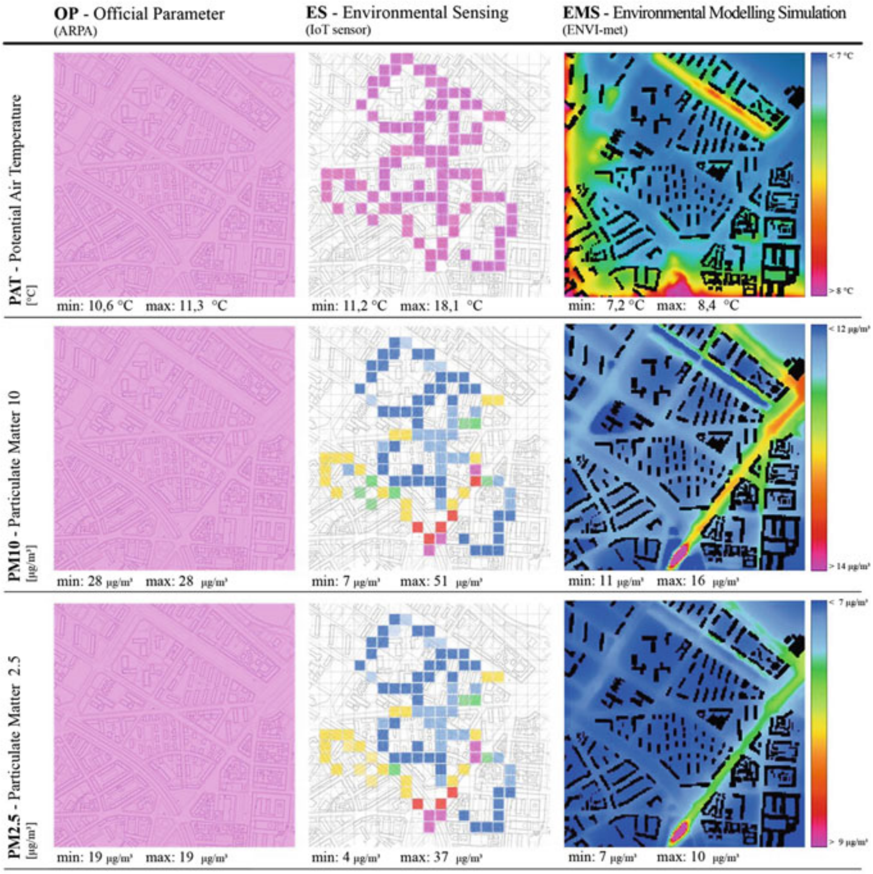

Fig. 82.7 Visualisation matrix at 3:00 P.M

instant conditions, while the simulation outputs rather highlight a certain trend, as they are based on traffic volume approximations. In these terms, sensors highlighted a higher PM concentration in some crossroads.

The research is burdened by several constraints. The simulation timing didn't allow us to model the area with a greater resolution. Although the main pollution sources are related to traffic, modelling other sources could have affected the total PM concentrations and the distribution pattern, as they finally account for ~ 15% of the total PM in November (Fig. 82.2). Besides, we could not force the wind speed and direction (apart from injecting initial values), as this would have required 30-min interval data. This may have affected the PM distribution and concentration, especially if we consider that the simulation day was characterised by highly variable wind speed and direction. As for the ES, we had to clean data, as some outliers were present. Finally, although necessary for data sampling and processing information, data acquired were overabundant, thus hard to manage.

82.5 Conclusions

The aim of the paper was to compare the results of an on-field measurement campaign with modelling and simulating, towards a site-specific assessment of the environmental quality in a real district. The originality of this research lays on performing an environmental assessment by combining ES and EMS, in mutual support for a comprehensive overview on several EPs. Both approaches "fed" from a CS experience, which is also meant to have a major role in sensibilising people towards more pro-environmental consciousness. The findings may encourage the extension of a network of sensors for a more accurate analysis of the urban environment conditions over time and space. This is especially true if we imagined a distributed sensor network for EPs and traffic monitoring, to be spread all over the city in parallel with respect to the official meteorological stations, supported by a proper IoT infrastructure. Indeed, these only provide hour data on a few EPs and a daily average values on PM concentration, which may actually strongly vary from one point of the city to another and cannot highlight any site-specific distribution pattern.

On the other hand, the on-site survey and acquired data were crucial for EMS. In this perspective, EMS could count on real-world high-resolution data, which may turn into a robust environmental time-series and "labelled" environmental conditions (i.e. hot summer day, rainy autumn day, dry spring day, etc.) for scenario assessment, design, and validation. This may finally lead to more and more accurate models, depending on-site-specific boundary conditions forcing. The finding may encourage expanding EMS to the whole city too, by discretizing the urban area to optimise the computational timing but still providing a space–time resolution allowing micro-urban scale analysis. Apart from the limitations described, EMS, supported by ES, plays a major role in knowing, thus representing input data to manage urban environmental conditions that may threaten health. Combining the approaches would finally lead to setting digital worlds for real cities, with a deeply site-specific perspective at the district scale, where the effects of policies, personal choices and habits, projects, anthropogenic processes, patterns of use are much more immediately visible and correlatable to human health and well-being.

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