Sensor monitoring experiences and technological innovations

D7.8

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List of abbreviations and symbols

ADC: Analog-to-Digital Converter is a system that converts an analog signal, such as a sound picked up by a microphone, into a digital signal.

AGLP: The Affero General Public License is a free software license.

AMSL: Metres Above Ground Level.

API: Application Programming Interface are a set of subroutine definitions, and tools for building application software.

ARIMA: AutoRegressive Integrated Moving Average.

CNC: Computer Numerical Control allows the automation of machine tools by means of computers executing pre-programmed sequences.

CSIC: Spanish National Research Council.

CS: Citizen Science.

ENOLL: European Network of Living Labs.

FFT: Fast Fourier Transform is an algorithm that samples a signal over a period of time and divides it into its frequency.

FMI: Finnish Meteorological Institute.

GBM: Gradient Boosting Machine is a machine learning technique for regression and classification problems.

GPIO: General Purpose Input/Output.

HDPE: High-Density PolyEthylene.

IAAC: Institute for Advanced Architecture of Catalonia.

IEC: International Electrotechnical Commission.

ISB: Individual Sensor Board.

JST: An electrical connector.
JRC: Joint Research Centre.

KWMC: Knowle West Media Centre.

LLS: Living Lab Stations.

MOS: Metal Oxide Sensor.

NDIR: Non Dispersive Infrared.

OLS: Ordinary Least Squares.

PCB: A Printed Circuit Board is an electronics circuit that mechanically supports and electrically connects electronic components.

REST: Representational state transfer is an architectural standard for web services.

RLM: Robust Linear Model is a form of regression analysis designed to overcome some limitations of traditional parametric and non-parametric methods.

RMS: Root mean square is the square root of the mean square (the arithmetic mean of the squares of a set of numbers).

RMSD: Root Mean Square Deviation is a measure of the imperfection of the fit of the estimator to the data.

SCK: Smart Citizen Kit.

SLA: A service-level agreement (SLA) is a commitment between a service provider and a client.

SPI: Serial Peripheral Interface (SPI) is a synchronous serial communication interface specification used for short-distance communication, primarily in embedded systems.

SPL: Sound Pressure Level.

SVR: Support Vector Regression.

TUDO: Technical University Dortmund.

TVOC: Total Volatile Organic Compounds.

UART: Universal Asynchronous Receiver-Transmitter is a computer hardware device for asynchronous serial communication.

UCD: University College Dublin.

UNIBO: University of Bologna.

USB: Universal Serial Bus.

UST: Universal Standard Time is a time standard based on Earth's rotation.

VOC: Volatile Organic Compounds.

1. Executive summary

This report presents the technical development and exploitation outcomes of the low-cost sensor technology developed as part of WP3: Passive Control Solutions. In the first chapter, we introduce the Smart Citizen ecosystem and its origins: an open hardware and software project around low-cost sensor technology that set the ground for the technological advancements developed during iSCAPE around low-cost sensors. Next, we introduce the methodology followed during the development and it's agile approach, to continue with the description of the two main hardware outcomes: the Smart Citizen Kit, aimed at CS and educational activities, and the Living Lab Stations, aimed at more advanced air quality research using low-cost sensor technology. The next chapter describes how the sensor design was reiterated after their usage with citizens in the Living Labs, and their deployment in the field in the case of the Living Lab Stations.

The results of the sensor evaluation in this deployment in the field are further discussed next, as well as the algorithms and models developed as a result of these activities. The results include a comprehensive analysis of the deployments from a data-driven perspective and provide techniques for advanced analysis of the sensor data. Next, we detail the commercial exploitation of the Smart Citizen Kit, available at a cost lower than €100, and with approximately 800 units sold at the time of writing this deliverable, alongside its future opportunities. Finally, we share various I outreach activities carried out during the project and discuss the conclusions / results of the technical development process.

2. Introduction

The use of low-cost sensors for air quality monitoring has seen a great increase in popularity during the past years. Drivers of this trend have been a pressing need for tackling the problem of outdoor air pollution, as well as the recent advancements in the field of sensors, digital electronics, and wireless communication technology. All this has led to the emergence of a new paradigm for air pollution sensing, and multiple research projects have explored the potential use of these type of sensors for this purpose. These activities have generally approached the issue in two different ways: from a Citizen Science (CS) and education perspective, where the primary purpose is to engage citizens in the measurement process and raise awareness of environmental concerns; or a more sophisticated scientific approach, where the main aim is to study the potentiality of the low-cost sensing technologies. These projects, however, have normally taken its own independent and in many cases, fully or partially closed approach.

In order to approach the air quality issue from a different perspective, the sensor innovations developed during iSCAPE (*WP3: Passive Control Solutions*) were based on low-cost sensor technology and aimed at exploring potential sensor utilisation for outdoor and indoor monitoring of pollution in a fully open approach. An open-source set of hardware and software tools was developed and used in sensor monitoring experiences for both scenarios: citizen scientists (*WP2: Living Labs*) and researchers (*WP5: monitoring and evaluation*). These experiences contributed to the improvement and design iterations of the sensing solutions, as well as the software tools around them. As described in the following sections, the openness and flexibility of this approach allows for an incremental development, ensuring technological solutions at each step of the project.

The initial sensor selection is based on *D1.5 (Summary of air quality sensors and recommendations for application)* and iterates over this sensor selection as advancements on the rapidly growing sensor technology become available. This design evolution is documented in this deliverable, and the sensor evaluation and calibration is also described in detail, aiming at providing guidelines for the sensor deployment and calibration. This is considered of great importance for the purpose of reproducible research, and for this reason, the tools for this analysis are also made open in the form of a Sensors Analysis Framework. In addition, this framework also ingests data from other open data networks such as local pollution data from the European Environmental Agency data.
This deliverable is summarising the comprehensive work being done over the last three years into one single document. D7.8 will serve as future guidelines for sensor experimentation and deployment. Finally, all the work presented is open and aims

to be maintained beyond iSCAPE. The goal aim is to generate new synergies, and foster those already existing with other EU funded platforms and research institutions.

3. Starting point

The sensor technology developed during the iSCAPE project bases its core design on the Smart Citizen project (detailed in section 3.1), an open hardware and software framework that aims at providing tools for environmental monitoring, ranging from CS and educational activities, to advanced scientific research. In this chapter, the origins and motivations of Smart Citizen are detailed, which set the bases for the hardware and software iterations developed during the iSCAPE project.

3.1 Smart Citizen introduction and origins

The Smart Citizen project[1] was born in Fablab Barcelona - IAAC in 2012, with the idea of providing tools to citizens to be more aware of their environment. In the context of rising popularity of IoT technologies aimed at the so called Smart Cities, the project focused on the environmental monitoring as a means of giving citizens a better understanding of their surroundings.

Figure 1. Smart Citizen Kit 1.1

[1] Smart Citizen Website: https://smartcitizen.me/

The hardware of the Smart Citizen project was firstly materialized on the Smart Citizen Kit (SCK): a modular stack of self-designed electronics with a set of low-cost environmental sensors and data logging capabilities. The initial versions of the kit were the SCK 1.0 and SCK 1.1[2]. These versions were later redesigned to the SCK 1.5 as part of the Making Sense H2020 project. At the same time, the original Smart Citizen software platform was completely rebuilt in 2016 after some components where built originally for the OrganiCity H2020 project. The original sensors in the SCK1.1 supported qualitative measurements of air quality (CO and NOx) via Metal Oxide sensors (MOs), light, temperature, humidity and noise readings. Data was logged via WiFi connectivity and sent to a dedicated API, or locally in a sd-card. The SCK1.1 is shown in Figure 1, in its original enclosure. The SCK 1.5 (shown in Figure 2) improved the hardware with a smaller footprint, better WiFi connectivity and logging capabilities, as well as better sensors for ambient monitoring. This was the starting point of the iSCAPE project.

Figure 2. SCK 1.5 with enclosure

3.2 Making Sense and OrganiCity

The Smart Citizen project was part of two European Commission co-funded research projects, generally targeted at participatory sensing and experimentation in cities. Making Sense and OrganiCity formed the foundation for the development of technological solutions for the iSCAPE project

[2] Smart Citizen legacy hardware: https://docs.smartcitizen.me/Legacy%20Hardware/

Making Sense[3] *- advances and experiments in participatory sensing (Grant agreement Nº: 688620)*, explored how open-source software, open-source hardware, digital maker practices and open design can be effectively used by local communities to fabricate their own sensing tools, make sense of their environments and address pressing environmental problems in air, water, soil and sound pollution. Making Sense allowed the Smart Citizen project to improve several aspects of the sensing hardware and to develop the SCK1.5, identifying critical barriers for citizens to get involved with the technology. This was then put in practise with better flows for sensor setup, by creating an application that contained instructions on how to assemble and set up the device for data collection (called on-boarding[4]). Finally, the guidelines for citizen sensing were published in a toolkit (also available for download[5]), which is shown in Figure 3.

Figure 3. Making Sense Citizen Sensing Toolkit

OrganiCity[6] *- co-creating smart cities of the future* (*Grant agreement No. 645198)*, explored how traditional smart cities could be enhanced with advanced software tools that could enable the experimentation of new services co-created by citizens

[3] Making Sense EU Project: http://making-sense.eu/
[4] On-boarding: https://start.smartcitizen.me
[5] Making Sense Toolkit: https://making-sense.eu/publication_categories/toolkit/
[6] Organicity website: http://organicity.eu/

and companies. For the project, IAAC developed a data exploration and presentation tool that worked as the foundation for the Smart Citizen platform front-end used in the iSCAPE project. This tool is shown in Figure 4.

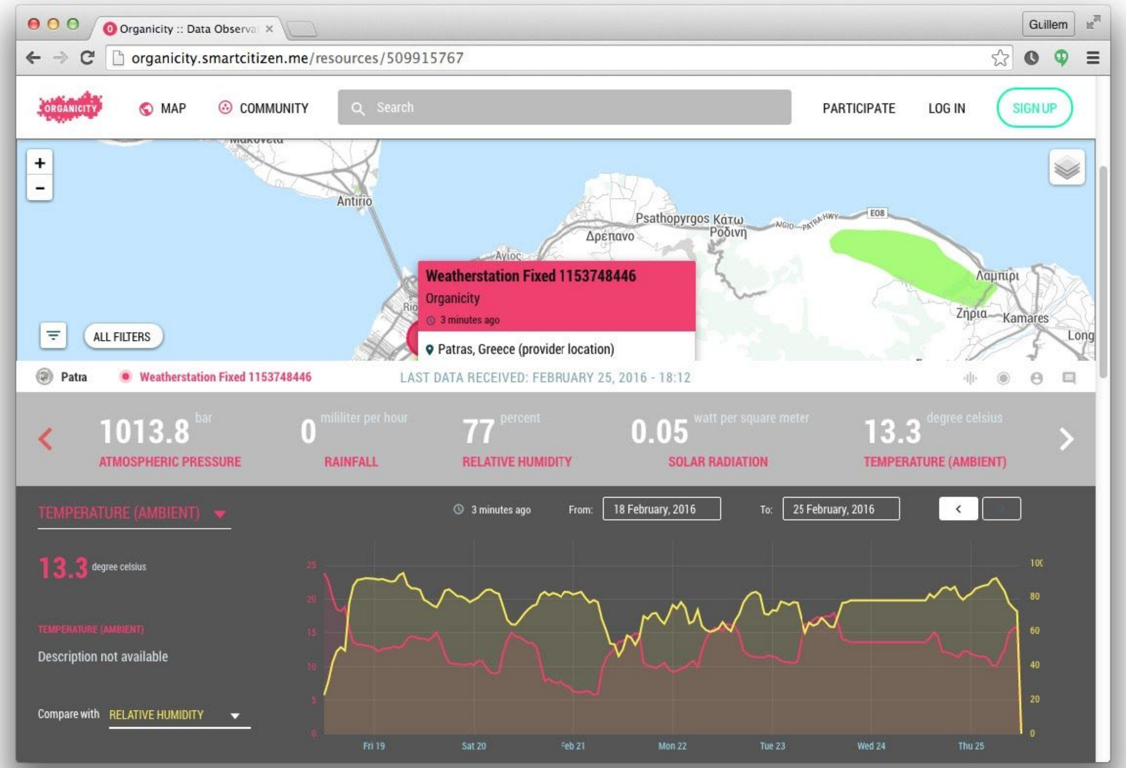


Figure 4. The Organicity Urban Data Observatory that leads to the current Smart Citizen front-end

3.3 Smart Citizen and iSCAPE

With the central aim of providing tools for users to measure and understand their environment, the Smart Citizen project focused its efforts on the air quality issue. The project started by making use of low-cost sensors for air quality monitoring focused on CS campaigns and educational purposes. Here the primary purpose was to engage citizens and raise awareness about environmental concerns.

In other projects that involved the use of low-cost sensors, the approach was to use them from a research-oriented perspective, where the main purpose was to study the potential of the low-cost sensing technologies for air quality monitoring. During iSCAPE, the Smart Citizen project used its experience in the CS field and broadened its scope by developing low-cost sensor technology, also suitable for scientific research. Based on the development carried out on previous projects and the extensive literature review in WP1, both CS and air quality research activities were targeted by providing a modular solution, with different ranges of sensors based on the same core components. Two solutions were developed: the SCK (2.0 and 2.1), intended for CS and awareness activities; and the Living Lab Station (LLS), designed to serve as a more complex and accurate set of air pollution sensors. The two solutions are described in chapter 4 of this deliverable.

In the context of openness and reproducible research, the aim of iSCAPE was to create a fully open and modular solution, that could be used by researchers in a cost-efficient and autonomous way. In comparison with other low-cost sensor platforms, this would be an advancement for researchers that aim to expand their set of tools for air quality monitoring. In comparison, other projects such as PurpleAir[7], EarthSense[8] or LuftDaten[9] provide a low-cost sensing solution that is capable of measuring various metrics, but that are limited to the manufacturer solution or are closed source. This open approach allows end-users to be part of not only the measurement activities but also of the analysis and development process. To summarize, the Smart Citizen project, in the context of iSCAPE, aims to:

1. Provide a low-cost sensing solution for CS and awareness activities, through the CS workshops.
2. Provide an open-source end-to-end solution for scientific development (sensing, data storage and data post-processing).
3. Provide an all-in-one educational tool that is both low-cost and open-source.

[7] Purple Air: https://www2.purpleair.com/
[8] Earthsense: https://earthsense.co.uk
[9] Luftdaten: https://luftdaten.info/en/home-en/

4. Design iterations

Throughout the different projects mentioned in the previous chapter, the Smart Citizen project developed several iterations of its set of tools, from SCK 1.1 to SCK 1.5. As mentioned above, the SCK 1.5 is the base version that the iSCAPE project started with, and which further evolved to SCK 2.0, SCK 2.1. and the LLS. In this chapter we describe the iSCAPE process specifically focusing on the agile methodology and the different design iterations.

The SCK was designed as the core element of a modular set of hardware components, on top of which the LLS was built. The LLS is meant as a tool for researchers to assess environmental metrics using low-cost sensors. Several studies (Hasenfratz et al. (2015), Schneider et al. (2016)) have concluded that the use of low-cost sensors for this purpose can provide better spatial and temporal measurement resolution for realistic assessment of personal exposure to pollutants with respect of high end sensors. With this in mind, the LLS was developed to deliver a fully open hardware and software solution.

4.1 Agile methodology: development, deployment and analysis

The methodology followed during the hardware and software development for the iSCAPE set of sensors can be best described as agile. Following an iterative and evolutionary processes, the hardware and software was designed in close collaboration with its end users. This approach, in comparison to a more linear one, allows greater flexibility during the technical development and design process. Each of the following sections describes how this methodology was implemented during different project stages.

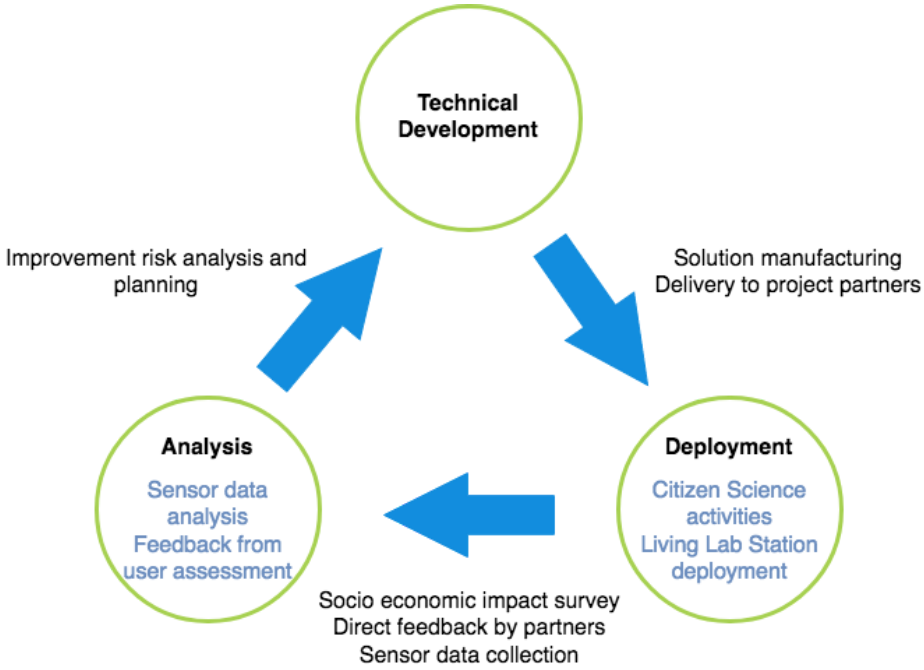


Figure 5. Methodological approach

The sensor technical development process involved a multidisciplinary team that worked in different tasks: planning, analysis, design, coding, unit and batch testing, deliveries and manufacturing. After each technical iteration, the development ended with a working solution that was then delivered to the iSCAPE project partners for deployment.

The deployment varied for each project milestone and solution. For instance, the SCK was mainly used in short deployments by the Living Labs within their CS activities, while the LLS were used in urban scenarios for longer periods. In the case of the LLS, those deployments were used to either understand and calibrate the sensors in them, for instance, with co-location with high end sensors, or to monitor Living Labs interventions (generally done at later stages of the project with a more mature hardware and software).

Finally, feedback was requested to both: citizens at the Living Lab CS activities, and research partners conducting LLS deployments, so that a validation stage could be conducted and the proposed solution could be assessed. The next project stage would then begin by improving the issues found and plan accordingly to solve them in following iterations. Figure 5 summarises this methodology.

4.2 Design evolution

Starting from the SCK 1.5, from Making Sense project, the initial versions of the SCK and the LLS were developed. The LLS was built upon the SCK by expanding its functionality. This included two additional pieces of hardware to which more sensors could be plugged through the SCK expansion port. These boards are the Gases Pro Board, which provides support for electrochemical sensors by Alphasense Ltd.[10], and the PM board, with a set of connectors supporting different communication protocols. The PM board is aimed at providing an off-the-shelf solution for PM sensors from Plantower, more concretely the PMS5003. More details about these boards are explained in section 4.2.1. Figure 6 provides an overview of the iSCAPE project iterations in a global project scale.

Throughout the project, the most important changes were those of the SCK hardware and firmware, which finally led to a commercially viable solution currently available at SEEED Studio[11], described in section 7.1. These iterations were mainly guided by the deployments conducted within the CS activities carried out by the Living Labs, and the feedback gathered from these activities, described in section 5.1.

The LLS also went through several design iterations. In particular, the most important effort was the development of an outdoor enclosure, which needed to handle the trade-offs between sensor exposure, ease of use, installation, and waterproofness. These features were improved through various deployments and direct feedback from the iSCAPE partners. These iterations are better described in section 5.2. The efforts conducted for data analysis and sensor post-processing are detailed in chapter 6.

[10] Alphasense Ltd. website: http://www.alphasense.com/
[11] Seeed Studio website: https://www.seeedstudio.com/

Figure 6. Project timeline for sensor development

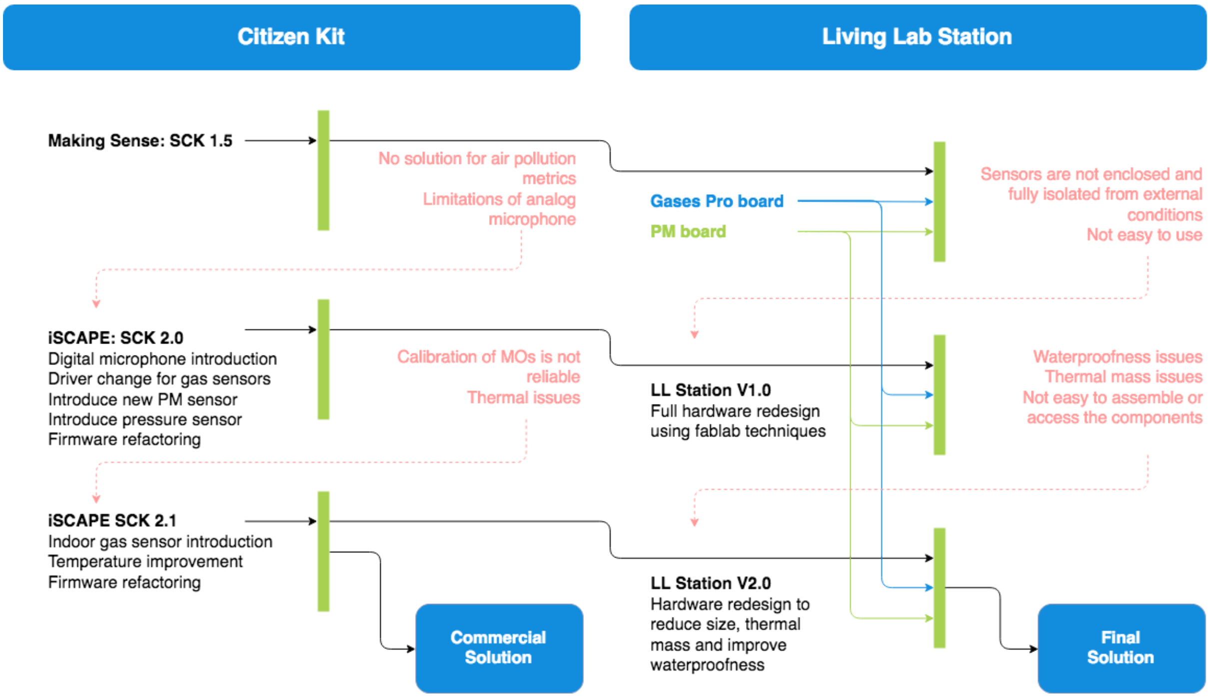


Figure 7. Overview of design iterations

Figure 7. describes the iterations of both, the SCK and LLS. For the purposes of measuring air quality within the iSCAPE project framework, these developments were determined by the following targets:

- Measurement of air quality needed to be divided between two sets of sensors: chemical composition sensors and particulate matter sensors. In the case of the SCK, these sensors were metal oxide sensors (MOs) and laser scattering sensors respectively. In the case of the LLS, a more accurate set of electrochemical sensors was used for the chemical composition sensors, as justified in the following subsection.
- Measurement should be accompanied with environmental sensors, such as temperature and humidity. This was decided after the review of the extensive literature regarding low-cost sensors, which use these measurements for correcting the raw readings of the targeted pollutant sensor in question.
- Raw measurements from the sensors, specially the air pollution sensors, should be available at all times, both in firmware level (inside the data board) and the sensor platform. This allows calibration algorithms to be tested and deployed by the development team or other researchers.
- Whenever possible, the sensors selected should be used in both, the SCK and the station, reducing development costs and time.

The sensor selection for each case will be detailed in the following subsections.

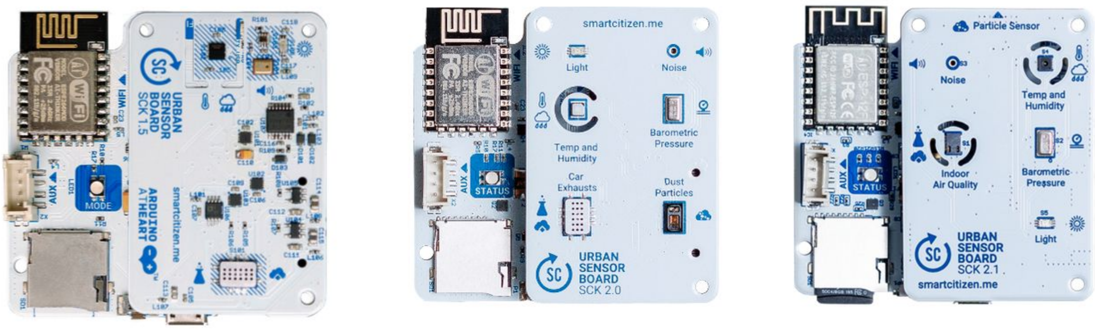


Figure 8. SCK Boards evolution (left: 1.5, middle 2.0, right: 2.1)

4.2.1 First prototypes development (enhancing SCK 1.5)

The initial design iterations for both, the Citizen Kit and Living Lab Stations were based on the SCK 1.5 version, derived from the Making Sense project. This version lacked several features for proper air quality assessment, and this set the initial steps for the redesign of the citizen kit into the SCK 2.0, and the development of two additional boards: the Gases Pro board and the PM board. These two additional boards were later included in the LLS described below.

All the SCK designs are comprised of two boards (Figure 8), the data board, which serves as a datalogger and provides WiFi connectivity and user interfaces (LEDs and buttons); the Urban Sensor Board, which holds the environmental sensors for urban monitoring, providing functionality for CS activities. For this reason, the data board has an auxiliary connector, to which different components can be branched. In this subsection, we will focus on the first iterations of the additional sensor boards, keeping the redesign of the SCK as a whole for the next subsection.

In the case of the LLS, the Gases Pro Sensor Board, shown in Figure 9, was designed as an auxiliary board with high-end potentiostatic circuits driving three Alphasense Ltd[12]. The final sensor selection is shown in Table 1. These electrochemical Series B Gas Sensors[13] are designed for ultra-low noise, high-performance, and low power consumption. This board includes an additional temperature and humidity sensor (Sensirion SHT31[14]), providing a measurement of

[12] Alphasense Ltd. Website: http://www.alphasense.com/
[13] Alphasense Series B Gas sensors: http://www.alphasense.com/index.php/safety/products/
[14] Sensirion SHT31 Datasheet: https://www.sensirion.com/fileadmin/user_upload/customers/sensirion/Dokumente/0_Datasheets/Humidity/Sensirion_Humidity_Sensors_SHT3x_Datasheet_digital.pdf

the actual temperature of the electrochemical sensors. Furthermore, an additional Grove[15] connector is included in the board to serve as an I2C[16] bridge.

Measurement	Units	Sensor
CO	*ppm*	Alphasense CO-B4[3]
NO_2	*ppb*	Alphasense NO2-B43F
OX (O_3 + NO_2)	*ppb*	Alphasense OX-B431
Temperature/Humidity	*ºC/%rh*	Sensirion SHT31

Table 1. Gas Pro Sensor Board Sensors

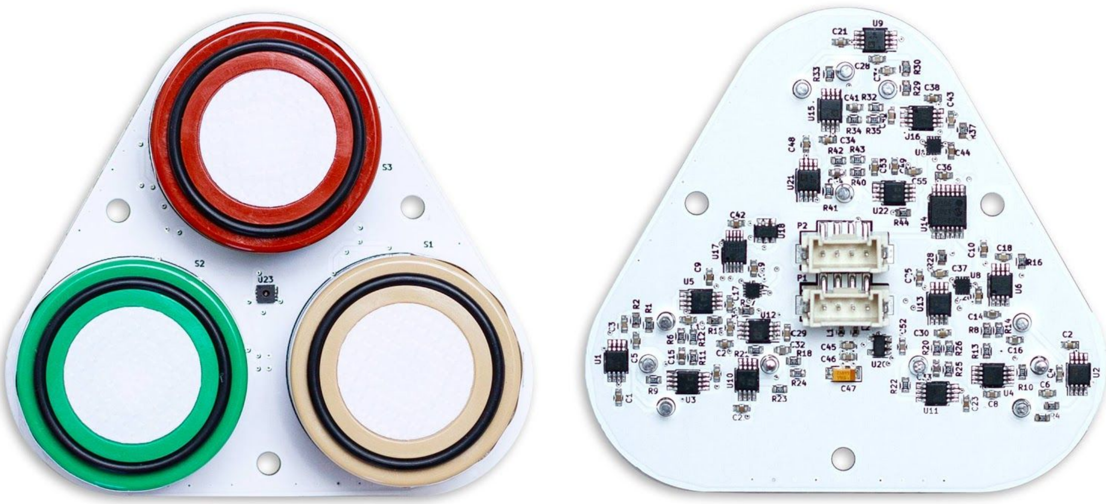


Figure 9. Gas Pro Sensor Board

The selection of the sensors was based on a wide variety of literature available on them, summarized as part of Deliverable 1.5. Both Penza and EuNetAir Consortium (2014) [1] and Mead et al. (2013) [2] test the NO2A1-A3 against reference instruments, in the laboratory as well as in the field, with well-correlated results. The former concluded that the Data Quality Objective for "indicative measurements" (European Parliament and Council of the European Union, 2008) [3] is fulfilled, and the latter report sensitivity in the low ppb region with high linearity. Spinelle et al.

[15] Grove by SEEED Studio: https://www.seeedstudio.com/category/Grove-c-1003.html
[16] I2C Specification: https://es.wikipedia.org/wiki/I%C2%B2C

2015 [4] tested the Alphasense NO2B4 and O3B4 in a field experiment, with various calibration approaches.

Performance evaluation of the same sensors was performed later including a test on a wide range of performance parameters (e.g. response time, calibration function, repeatability, drift, hysteresis effect, and matrix effect) (Spinelle et al. 2017) [5]. The experiment found a strong correlation with reference instruments (R2 > 0.9) and identified some cases with significant hysteresis effect related to humidity. In chamber conditions, the performances of the Alphasense CO-B4 was found to be excellent, with the R2 values being greater than 0.9 (Castell et al. 2017 [7]; Mead et al. 2013 [2]; Sun et al. 2016 [6]). Two field studies reported moderate to excellent R2 values (0.53-0.97) for the CO-B4 sensor (Castell et al. 2017 [7]; Mead et al. 2013 [2]). Finally, some calibration approaches as detailed in Popoola et al. (2016) [8] and Hagan et al. (2018) [9] which are used in the post-processing stage as a basis for pollution concentration calculations.

Furthermore, the LLS is completed with the addition of the PM Sensor Board. This board was designed as an auxiliary board capable of managing a wide variety of connections, aiming to connect several sensors and handle it's acquisition. It is mainly intended to serve as an I2C bridge between the data board and several other types of sensors, additionally provide an off-the-shelf connection to the Plantower PMS5003[17] sensors supporting JST-XH connectors (see below for the selection criteria). This board was designed to serve as a hub, with a standard set of Grove Connectors, including an I2C bridge, a 12bit ADC (analog to digital converter), GPIO (general purpose input output) pins and UART (universal asynchronous transmitter receiver) interfaces. An image of the PM Board is shown in Figure 10.

The Plantower PMS5003 sensors were selected explicitly due to the sensor benchmarking done as part of Deliverable 1.5 into low-cost solutions and further evaluations by academics in the field (Sayahi et al. [19], Jayaratne et al. [20], and Badura et al. [21]). The PMS5003 uses the most common type for low-cost PM measurement, which is based on light scattering. This type of sensors measure suspended particulates by employing a light beam and a light detector set to one side (often 90°) of the source beam. Particle density is then a function of the light reflected into the detector and the particle mass is a calculation derived from this density, assuming certain properties of the particles, such as shape, color and reflectivity, among others. While the selected sensor presented a good trade-off between cost, complexity and measurement accuracy, other sensors could be used for PM measurement, since the technological advances in the field have been

[17] Plantower PMS5003: http://www.plantower.com/en/content/?108.html

frequent in recent years. For this purpose, the PM board is aimed to serve as a boilerplate for experimentation and easy implementation of other sensors.

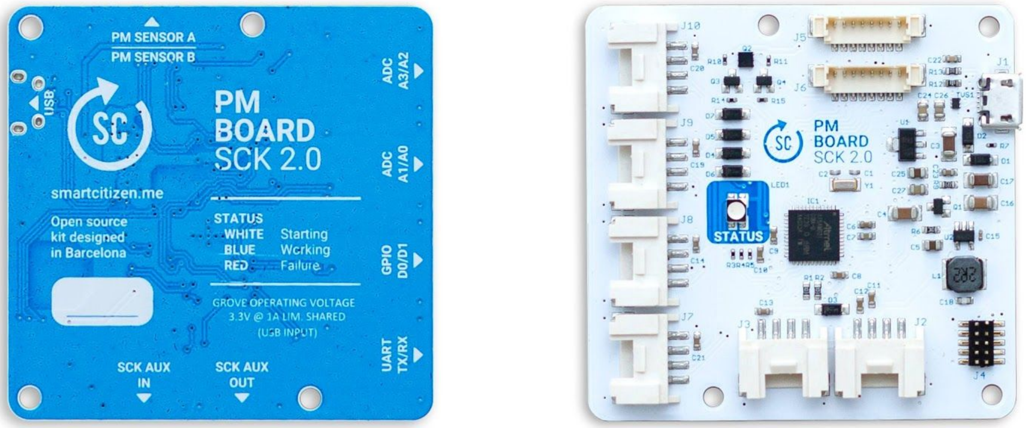


Figure 10. PM Sensor Board

In Figure 11, the connection of the Gas Pro Board and the PM Board, with two PMS5003 sensors, and one SCK is shown. With these two boards, the lack of a robust air pollution solution was addressed in the context of the iSCAPE project, by measuring three of the most common type of chemical pollution in urban environments: CO, NO_2 and O_3. This approach also allowed to employ similar methodology in sensor calibration, since all three sensors use two electrodes for their readings.

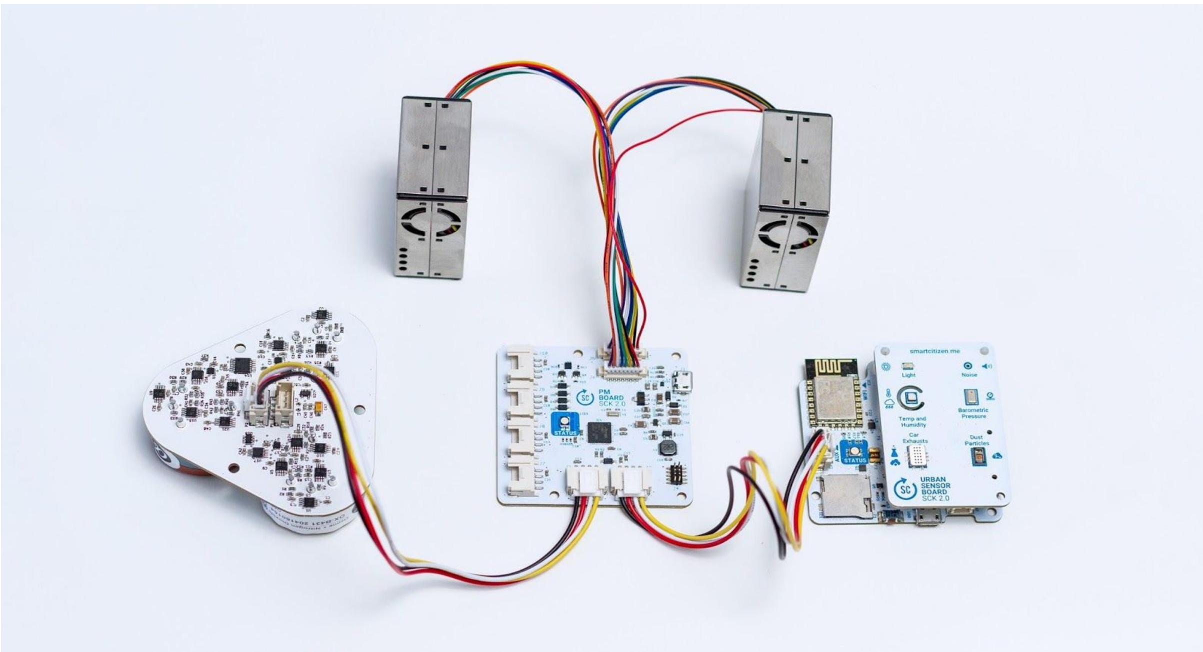


Figure 11. Enhanced air quality solution connexions

4.2.2 Full redesign (from SCK 1.5 to 2.0)

The solution presented in the previous subsection features three main sets of sensors: environmental, chemical composition, and particulate matter. This solution, with the introduction of the three electrochemical sensors and two additional boards, poses a significant increase in cost with respect to that of the SCK. Understanding the SCK as a light-weight version of the station, the need for a better solution for air quality monitoring needed to be addressed.

The SCK 1.5 was redesigned with the following objectives for environmental measurements:

- Chemical composition should be measured, at least with indicative measurements, with the MOs (SGX MICS 4514)
- Particulate matter should be measured with the same type of sensor as in the LLS
- Noise measurement could be improved, to be able to offer a compensated Sound Pressure Level (SPL) in different scales (dBA, dBC or dBZ)
- Temperature and humidity readings should be improved, since in SCK 1.5 they were understood to have approximately 1ºC bias

Significant changes were also added to the operational circuits in the data board, in particular, introducing a better battery charging control. The driver for the metal oxide sensor (SGX MICS4514) unit also was fully redesigned in order to improve its behaviour. However, the complexity of this solution and the hardware iterations required a reliable measurement with low noise, and temperature affectations obliged the development team to find a new solution, which will be detailed in the following chapter.

The PM sensors in this SCK iteration were also the Plantower PMS5003 sensors. These sensors use a JST-XH connector and are powered at 5V, while the electronics of the SCK operate at 3.3V. For this reason, the required connector and voltage step-up were included in the Urban Board. An additional sensor was also included in the Urban Sensor Board: MAXIM MAX30105. This sensor is not a PM sensor, and uses a different measurement principle in comparison with the PMS5003. However, it was included for experimentation with the sensor, as it had been used by others for this purpose. This sensor was later on discarded, due to the calibration effort needed and the ease of use of the Plantower PMS5003.

Temperature and humidity readings were also addressed by adding a more accurate sensor: Sensirion SHT31, which provides a wide measurement range, high resolution and long-term stability, and it represents an upgrade from previous versions in terms of reliability and accuracy.

Finally, noise readings were also improved with the SCK2.0. In previous versions, an analog microphone (BH1730FVC[18]) was used for sound pressure level SPL measurement. This solution only allowed for instantaneous SPL readings, but it wasn't possible to sample at high frequencies. The microphone was replaced by a TDK (former Invensense) ICS43432 I2S MEMs microphone, which allows for high frequency sampling at 44.1kHz. This improvement was accompanied by a significant firmware and testing development effort, with the aim of extracting a noise spectrum (dB SPL vs. frequency) by using a Fast Fourier Transform (FFT) algorithm. The resulting spectrum could then be weighted in order to obtain SPL in different scales, being the most commonly used dBA and dBC, which are a representation of human hearing models. The noise spectrum is also available for analysis.

Table 2 summarizes the sensor changes between SCK 1.5 and SCK 2.0.

Measurement	SCK 1.5 Sensor	SCK 2.0 Sensor
Temperature / Humidity	Sensirion SHT21	Sensirion SHT31
Noise and noise spectrum	Knowles SPU0414HR5H (only SPL)	TDK ICS43432
Particulate Matter	n/a	Plantower PMSX003
Chemical composition	SGX MICS4514	SGX MICS4514 (driver change)

Table 2. Smart Citizen Kit 1.5 to Smart Citizen Kit 2.0 sensor changes

4.2.3 From citizens to researchers (Living Lab Station Development)

The initial iteration of the LLS is shown in Figure 12. The enclosure of this version was later redesigned using digital fabrication techniques. Using a series of layered HDPE milled blocks in which the different components were placed. The unit was designed for outdoor functioning, and the results of its evaluation and further iterations are shown in chapter 5 of this deliverable. The materials of the enclosure are low-density HDPE, easily machinable in a 2.5-axis CNC and laser cut acrylic

[18] BH1730FVC datasheet: http://www.farnell.com/datasheets/1813319.pdf

cover. The main principle for this design is to allow for its easy fabrication within a Fablab[19]. As detailed in chapter 5, this iteration will later have waterproofness issues, which were redesigned into the last iteration of the device.

Figure 13.a shows an actual deployment of the station, while Figure 13.b shows an exploded view of it. This later version of the LLS also included a dedicated power supply. This allowed users to power the device with a normal 230V AC supply, a 5V DC possibility was also available. This version of the LLS was manufactured and delivered to the six iSCAPE Living Labs for evaluation.

Figure 12. Initial iteration of Smart Citizen Station with SCK 1.5

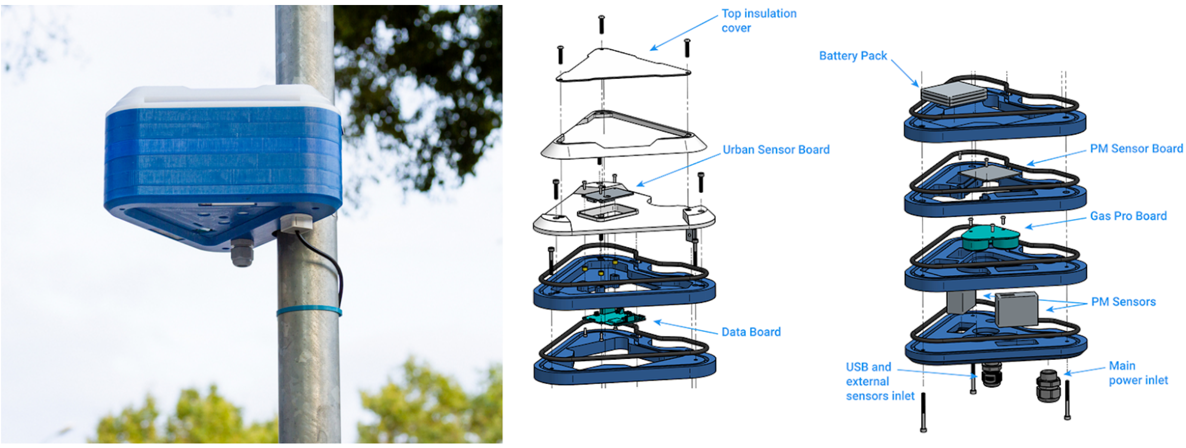


Figure 13a (Left) Living Lab Station in action. 13b (Right) LLS exploded view

[19] Fablab: https://en.wikipedia.org/wiki/Fab_lab.

4.3 Software evolution

Accompanying the set of hardware tools described in the previous section, dedicated software solutions were developed as part of the Smart Citizen project prior to the iSCAPE project. This software solutions range from a dedicated API and a sensor platform in which users can store their data, visualise it and manage their devices, to a set of more advanced analysis tools for sensor analysis. This section describes both, especially focusing on the iterations done within the iSCAPE project with regards to the sensor data analysis.

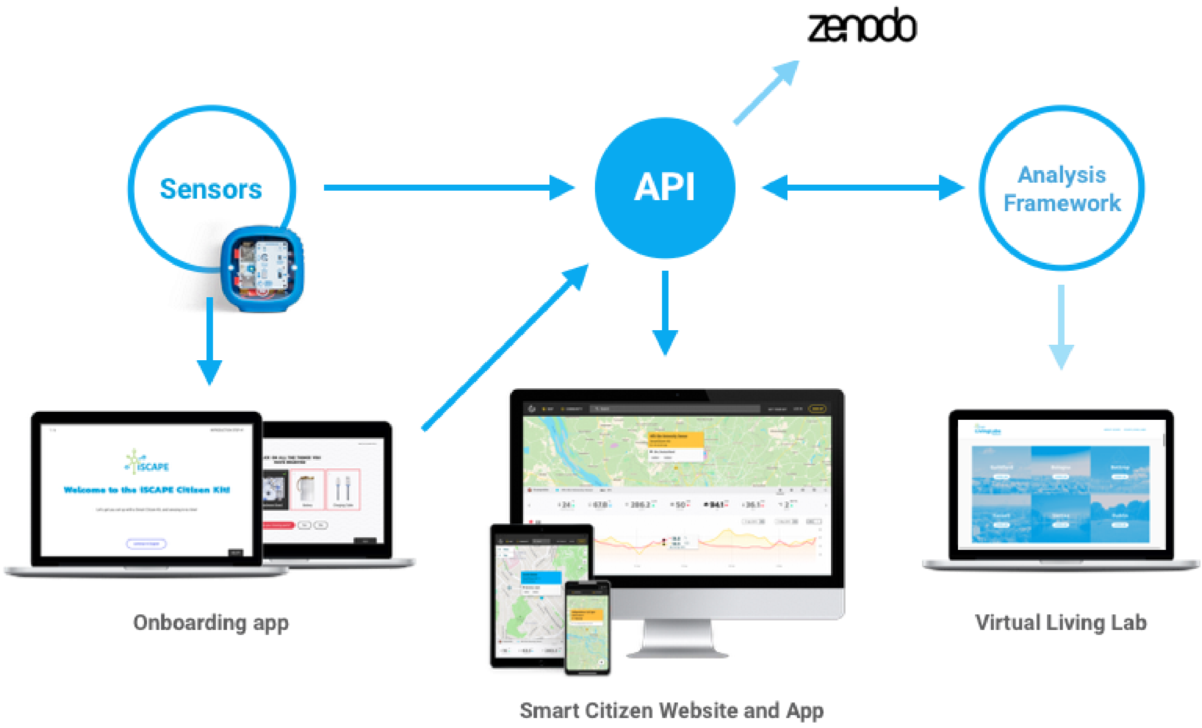


Figure 14. Software architecture

4.3.1 Sensor Platform

The sensor platform is comprised of three main software components and its architecture is shown in Figure 14. All the components are released on AGLP-3.0 open-source license and ready to be deployed on any standard cloud infrastructure.

- Smart Citizen Website[20]: it aims to provide a visual website where the project environmental sensors can be accessed in near real time to facilitate the exploration of data with other contextual data (maps, keywords) and processed reports. This is especially important towards citizens engaging at

[20] Source Repository https://github.com/fablabbcn/smartcitizen-web

each local site having a sense of ownership over a technology intervention has been associated with sustained community engagement (Balestrini et al. (2014) [14]). The main instance is available at smartcitizen.me/kits.

- Smart Citizen API[21]: the platform provides a REST interface for all the functionalities available on the Website. That allows applications to be developed on easily on top having access to all the features to create complex and rich tools. The main instance is available at api.smartcitizen.me.
- Onboarding app[22]: aimed at facilitating the process of sensor setup to ensure that users, irrespective of their technical expertise, can install the sensors. It guides the user through the process of the setup using a simple and visual graphic language. It is built as a separate tool from the core Smart Citizen Website in order for it to be customized for each deployment. It exchanges data with the core platform using the Smart Citizen API. The main instance is available at start.smartcitizen.me. and contribute to the source.

The three main software components existed before the ISCAPE project. However, significant changes were required to match the performance and functionalities required by the project:

- Improvements of the application data framework to support multiple sensor types and algorithms through the Sensors Analysis Framework, some sensor data is processed after it is received.
- Providing support for uploading sensor data collected on an SD card; some sensor data in ISCAPE gathered data offline.
- Interactions on the Onboarding UI to help new users configuring and manage new devices. The existing software was only a proof of concept and required a significant refactoring to increase maintainability. The UI was improved based on users feedback collected during the multiple project workshops in each of the Living Labs.
- Improvements on the overall stability and performance of the platform to guarantee an service level agreement (SLA) of >99% by improving the infrastructure management tools.

A more detailed description of the complete software architecture and the specific parts components developed and/or upgraded as part of the ISCAPE project is

[21] Source Repository https://github.com/fablabbcn/smartcitizen-api
[22] Source Repository https://github.com/fablabbcn/smartcitizen-onboarding-app-start

available in report *D3.5 (comprehensive) Real Time Reporting System for Monitoring with Sensor Technologies.*

4.3.2 From hardware to algorithms

The use of low-cost sensors for air pollution monitoring is subject to the proper data analysis of the raw sensor readings. Within the iSCAPE project, a data driven approach was followed, with the development of a framework for sensor analysis and calibration. This framework was initially meant as a set of tools that iSCAPE partners could use for accessing the Smart Citizen API to explore the sensor data, but later on it evolved to a more complex toolset for sensor model development, data visualisation and data analysis in a programmatic way.

The framework was built using Python[23], an easy to use and powerful programming language that can handle large amounts of data, and is largely used in the data science community. The code is fully open-source and is hosted in a Github repository. Documentation for its use can be found in the official documentation, with several tutorials and user guides ranging from data exploration and organization, to complex machine learning model analysis and model development. A detailed list of the possibilities within the framework is listed below:

1. Tools to retrieve data from the Smart Citizen's API or to load them from local sources (in csv format, compatible with the SCK SD card data).
2. A data handling framework based on the well known pandas[24] package.
3. A set of exploratory data analysis tools to study sensor behaviour and correlations with different types of plots.
4. A sensor model calibration toolset with classical statistical methods such as linear regression, ARIMA, SARIMA-X, as well as more modern Machine Learning techniques with the use of deep learning networks, RF (Random Forest), SVR (Support Vector Regression), GBM (Gradient Boosting Machine) models for sequential data prediction and forecasting.
5. Methods to statistically validate and study the performance of these models, export and store them.
6. Interface to convert the python objects into the statistical language R.

This framework is not only aimed to be a set of tools for offline data analysis, but also to be included as a pipeline for online sensor data processing. The available sensor platform and API allows for a full integration of these features, as well as a continuous improvement of them, should more calibration deployments be conducted in the future.

[23] Python is an open-source all-purpose language. More information here https://python.org
[24] Pandas package: https://pandas.pydata.org

5. Working with end users

The SCK and LLS described in the previous section were delivered to the iSCAPE partners for usage in the CS activities or sensor evaluation in the field. During these activities, a significant amount of data and user feedback was collected. Following the iterative methodology described above, this information was assessed and used for improving different aspects of both the SCK and the LLS. In this section, the different lessons learnt and solutions are detailed, ranging from hardware improvement to usability iterations and documentation. This stage is considered to be of great importance for the development process, based on the experience gained in other projects such as Making Sense, which used constant user feedback for the development of CS tools and methods (Balestrini et al. (2017) [13]).

5.1 Learning from citizens

Several CS activities were carried out by the Living Labs, as reported in Deliverable 4.7. These activities involved workshops with citizens that used the SCKs, for data collection, and later on analysed their findings with the help of the Living Lab team. During these activities, the feedback was collected by means of a survey prior and post to each activity and passed over by the Living Labs coordinators, in the Socio-Economic Assessment survey also available in this deliverable. In addition to these feedback channels, feedback collection was included for more comfortable feedback and traceability. All this information was assessed to identify future improvements, and it is summarised in Table 3, which shows the most critical feedback collected from from the development perspective during iSCAPE CS activities.. The diagnosis column of this table describes a summary of action taken when applicable, being left for future opportunities, out of the iSCAPE Project. Each of the items in this table is further described in the following paragraphs.

Feedback	Category	Diagnosis
Temperature / Humidity readings are biased	Hardware - Data reliability	Hardware issues provoke biased temperature/humidity readings
Lack of enclosure for outdoor exposure	Hardware	Hardware redesign implies further effort on enclosure definition
Pollution data calculation	Data post-processing	Lack of reliable data for

		actual pollution calculation
Sensor mobility	Location add-on	No - Future opportunity
	Enclosure redesign	No - Future opportunity

Table 3. CS activities feedback

Temperature and humidity readings were found to be affected by the regular operation of the SCK2.0 due to the hardware changes mentioned above. That led to a temperature increase that was characterised and found to be on average between 3-6ºC, depending on the operation mode of the device (charger connected or not, network publication or not). That also led to a decrease in relative humidity between 5-15%. Counter measures were applied for this issue with regards to hardware design as a long term solution, as well as firmware improvements to try and minimise the temperature affectation from the sensor operation. That was considered as an essential user perception issue, since the temperature is one of the few metrics users have a common understanding of, and this could lead to data mistrust, even if the other metrics were not affected. The heat sources were analysed and corrected, as summarised in Table 4 below.

Heat Source	Countermeasure	Short term applicability
PM sensor activation	Hardware redesign	No - SCK 2.1
	Firmware correction	Yes
MOS sensor activation	Hardware redesign: MOS sensor replacement	No - SCK 2.1
Battery charging	Hardware redesign	No - SCK 2.1
	Firmware correction	Yes

Table 4. Temperature heat sources and countermeasures

In particular, the hardware changes will be detailed in the following chapter. Firmware changes were mainly directed towards reducing the temperature effect of the sensor operation, and by spreading out their operation, in other words, temperature and humidity are always measured in the coldest conditions, before the other sensors are turned on. Additionally, a firmware adaptation was designed in order to assess the effect of the enclosure on the greenhouse effect provoked by the electronics being encapsulated in a confined space. This strategy turns off the device periodically and cools it down, aiming to determine the temperature offset between regular operation and cooled downstate, which is then subtracted from temperature readings (or added to humidity) as a static offset.

In addition to the issues from temperature, the enclosure for the sensors was key feedback from the CS participants, as well as from Living Labs themselves. The enclosure had to be entirely redesigned from the original version (SCK 1.5, Figure 15a.) to one that could hold the PM sensor, as well as to confine less the sensors (Figure 15b). An early deployment was initially not viable due to time constraints, and several iterations were performed before a solution could be finally delivered. This new enclosure also made the kits rainproof, and hence deployable in outdoor conditions.

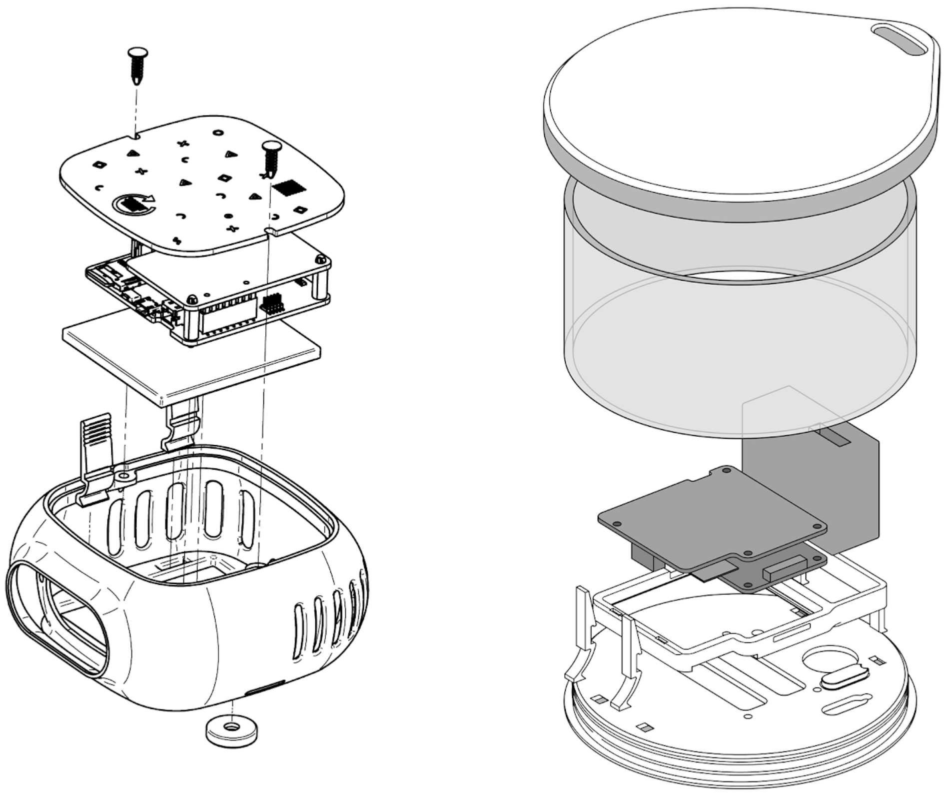


Figure 15.a and 15.b Enclosure evolution from SCK1.5 to SCK2.1

These enclosures were manufactured following digital fabrication techniques available at a Fablab. This involved the use of CNC milling, 3D printing and laser cutting. The designs are fully available[25] to download and replicate by others. In addition to the official design, several other iterations were also developed, for

[25] Enclosures repository: https://github.com/fablabbcn/smartcitizen-enclosures

instance, only using 3D printing as a fabrication technique (Figure 16). Figure 17 shows the final iteration of the enclosure for CS.

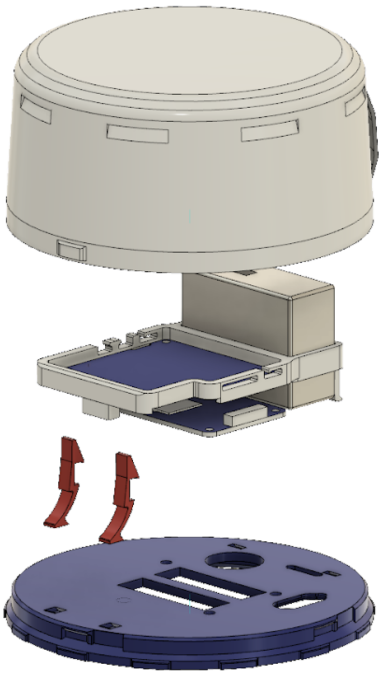


Figure 16. 3D-printed enclosure for SCK2.1 with Plantower PMS5003

Figure 17. 3D-printed enclosure for SCK2.1 with Plantower PMS5003

5.1.1 Improving the sensors in the SCK

Air pollution low-cost sensors generally requires critical data post-processing in order to make sense of the raw sensor data. The MOs installed in the SCK1.5 and SCK2.0 were particularly affected by temperature and humidity variations, and their specific calibration was attempted by the analysis of the available literature and test data. A generic sensor calibration was not feasible, since sensor-to-sensor variations are unknown and not deterministic, and a calibration per sensor required of vasts amounts of testing that has been shown to be not replicable, nor durable by others (Peterson et al. (2017)[14]). For this reason, an indicative measurement should be expected for MOs, and this led to an assessment of different already available solutions that could provide better measurements. The sensors available at the moment of the SCK 2.1 redesign are stated in Table 5.

Sensor	Indoor/Outdoor	Type	Interface	Consumption (mA)
Bosch BME680[26]	Indoor	T, H, P, VOC, eCO2	I2C and SPI	12
SGX VZ89[27]	Indoor	Voc, eCO2, eCO2	I2C	38
SGX 6814[28]	Outdoor	NO_2, CO, NH_3	Analog	60
AMS CCS811[29]	Indoor	VOC, eCO2, *(T, H auto compensated)*	I2C	14
AMS CCS801[30]	Indoor	VOCs, eCO2 *(T, H auto compensated)*	I2C	10,3
AMS AS-MLV-P2[31]	Indoor	VOCs, CO	Analog	10,3

[26] https://cdn.sparkfun.com/assets/a/3/5/0/4/BME680-Layout_Considerations.pdf
[27] https://www.sgxsensortech.com/content/uploads/2016/07/MiCS-VZ-89TE-V1.0.pdf
[28] https://www.sgxsensortech.com/content/uploads/2015/02/1143_Datasheet-MiCS-6814-rev-8.pdf
[29] https://ams.com/ccs811#tab/documents
[30] https://ams.com/ccs801#tab/documents
[31] https://ams.com/documents/20143/36005/AS-MLV-P2_DS000359_1-00.pdf

Sensirion Multi-Pixel[32]	Indoor	eCO2, VOC	I2C	48
UST Sensor IAQ5000[33]	-	CO2	I2C	48

Table 5. low-cost MOS sensor benchmarking

As mentioned above, the sensor available in the SCK2.0 was the SGX MICS 4514, capable of reacting to CO and NO_2, with an analog interface. The SGX MICS 4514, and none of the sensors shown above are fully deployable in outdoor conditions for air pollution sensing due to cross-sensitivity to other pollutants and temperature/humidity variations. This fact, in addition to the above mentioned issues about data mistrust, led to the design simplification of the Urban board 2.1, selecting the AMS CCS811 as a proper trade-off between implementation effort, consumption, metrics available and deployability. The final list of sensors for the SCK 2.1 is shown in Table 6.

As mentioned above, several additional hardware design decisions were reconsidered, in particular to improve temperature behaviour of the SCK, battery charging, and the above mentioned MOs. These improvements in hardware reduced the temperature offset from the 3-6°C range to the 1-3°C range, depending on the mode of operation. To compensate this remanent error, the firmware corrections presented above still apply for this version.

Sensor	Environment	Type	Application
Sensirion SHT31	Indoor/Outdoor	Environmental	Temperature and relative humidity
Invensense ICS-434342	Indoor/Outdoor	Noise pollution	Noise Level and FFT Spectrum
Rohm BH1721FVC	Indoor/Outdoor	Environmental	Ambient Light (directional)
NXP MPL3115A26	Indoor/Outdoor	Environmental	Barometric pressure, AMSL
AMS CCS811	Indoor	Chemical	eCO2 and TVOC

[32] https://www.sensirion.com/en/environmental-sensors/gas-sensors/multi-pixel-gas-sensors/
[33] https://www.diytrade.com/china/pd/12876368/IAQ5000_Indoor_Air_Quality_Module.html

		composition	
PMS 5003	Indoor/Outdoor	Particulate Matter	Particulate Matter (external)

Table 6. SCK2.1 list of sensors

5.1.2 Building community

In addition to the Living Lab activities, a community of users from previous SCK versions was actively maintained in the Smart Citizen forum[34] and Github repositories[35]. Feedback and contributions from these users was followed-up and integrated when necessary. This active community of users is core to the further exploitation activities detailed in the related chapter of this deliverable. An example of some user contributions is shown in Figure 18.

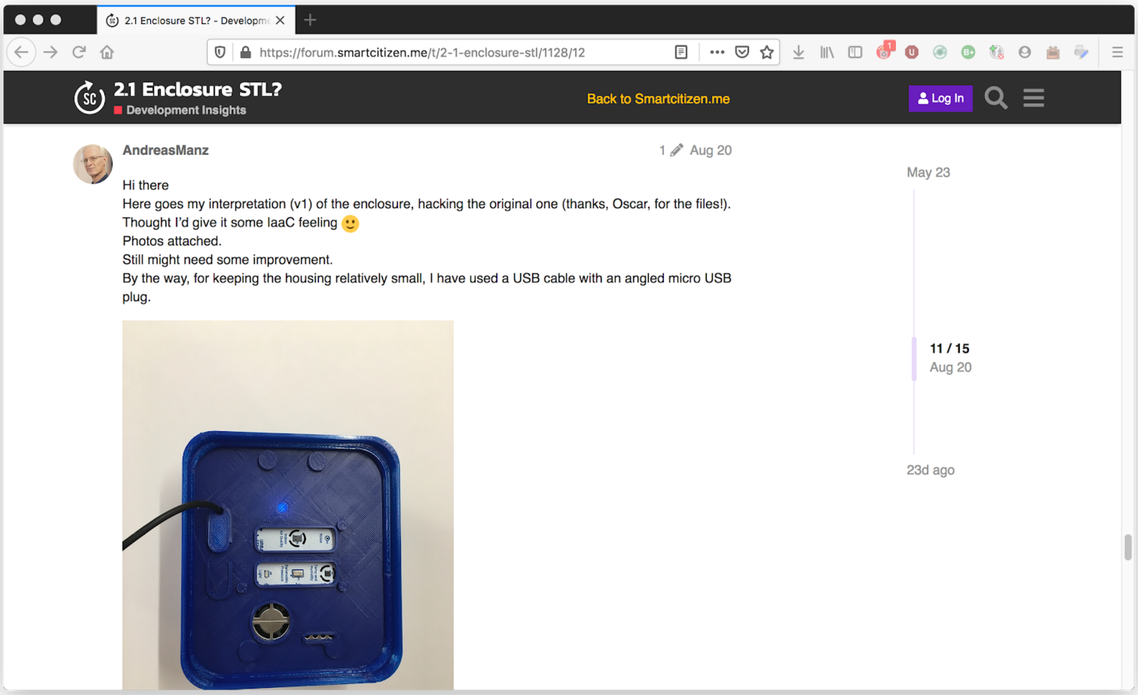


Figure 18. Example of user contributions

5.2 Learning from scientists

In addition to the feedback provided by the users from the operation and sensor data for the Citizen Kits, the LLSs were also subject of validation during several

[34] Smart Citizen Forum: https://forum.smartcitizen.me
[35] FablabBcn Github repository: https://github.com/fablabbcn

campaigns in the sites of Bologna, Dublin, Surrey and Hasselt. These campaigns included several deployments that accumulated not only sensor data but also feedback about sensor operation, usability testing and installation.

A first set of LLS was delivered to six iSCAPE Living Labs for an initial evaluation during the months of January and February 2018 (shown in Figure 12 above). The solution included a SCK 1.5 sensor with a Gases Pro Board attached. The enclosure for this solution was an off-the-shelf design using a chimney extractor component, with in-house fabricated holders for the electronic components. The primary objective of this evaluation was to assess the initial solution for gas measurement in outdoor conditions, particularly focusing on reliability. The maturity of the sensors hardware and firmware at this point of the project didn't yield a sufficient amount of data for sensor performance evaluation, but a very valuable information was retrieved for further redesign of the SCK into 2.0 and the LLS, improving the enclosure for better waterproofness and the firmware with regards to stable data collection.

A second design iteration was delivered to all iSCAPE partners during the last term of 2018 and the beginning of 2019. This evaluation focused not only on the hardware reliability, but also on the sensor performance, see summary in Table 7. For this purpose, several sensor co-locations where planned with partners that had access to high-end scientific instrumentation and a specific protocol for calibration was developed.

The protocol for sensor evaluation included a sensor stabilisation period of at least two weeks for electrochemical sensors, and recommendation for installation and use, such as height, sun exposure avoidance, temperature and humidity stability, among others. The evaluation focused on real-world conditions calibration, under a wide range of exposure and climatic conditions, rather than developing tests in controlled conditions, as prior studies show discrepancies in the accuracy resulting from evaluation in laboratory conditions, versus that of outdoor conditions [7][4][5]. The tests were conducted by co-location of at least two stations per site with high-end sensors. The duration of the tests was of at least 2,5 months, with two location changes. This was a compromise between the indications given in (Spinelle et al. [10]) for at least 3-months campaign and the availability of high-end sensors for the evaluation. The campaign intended to cover a range of conditions by the deployment of the Living Lab Station in diverse conditions, not only climatic but also exposure-wise. The location changes were also intended to evaluate how well the sensors were able to adapt to this exposure and climatic changes [11]. All the data was uploaded to the Smart Citizen Platform and was analysed using the Sensor Analysis Framework described above.

Partner	Date	Number of LLS	Purpose of evaluation	Actual outcome
UNIBO	07/2018	2	Calibration	Calibration during the month of August 2018 on one site, while evaluating photocatalytic coating
UCD	10/2018	2	Calibration	Calibration in two different locations (Urban Background and Traffic)
UoS	10/2018	4	Monitoring intervention	Monitoring of green infrastructure in two different locations for >6 months
FMI	10/2018	2	Calibration	Calibration in two different locations (Urban Background and Traffic)
UH	10/2018	2	Monitoring intervention	Monitoring of air quality in the vicinity of schools in the city of Hasselt
TUDO	10/2018	2	Calibration	None

Table 7. Second delivery of LLS evaluation details.

The following paragraphs will focus on the deployment and hardware evaluation, while the analysis of this data for sensor performance evaluation will be discussed in section 6.3.

A summary describing the most relevant issues regarding the LLS found during these deployments is shown in Table 8.

Feedback	Category	Diagnosis
Waterproofness	Hardware	Design is not fully waterproof and moist can leak in to the power supply and sensor area
Temperature effect on sensor robustness	Hardware - Data reliability	Design has a high thermal inertia
Access to SD card	Hardware	Design is too complicated for easy access to SCK
Connectivity / Battery Duration	Hardware	Connectivity and battery duration are limited

Table 8. Living Lab Station Summary Feedback

The modular design shown Figure 13. led to waterproofness issues that were the reason to recall all LLSs at the beginning of 2019. The HDPE layers of the device were not fully sealed, and in weather conditions such as those found in Guildford or Dublin sites, moist provoked several units to fail. A major redesign was carried out for the following LLSs. The recalled units were sealed manually with gaskets and redelivered for evaluation. Furthermore, a custom cover was developed and delivered to all partners and is shown in Figure 19.

Additionally, the power supply was fully redesigned, with a custom in-house designed PCB (Figure 21). To avoid safety issues, the power supply was mounted in an IP65 box, externally attached to the mounting point of the station as seen in Figure 20. This allows the body of the station to work at 5V, with no risk of high voltage manipulation or moist leaking into the supply area.

Figure 19. Cover and external temperature sensor

High thermal mass of this version provoked large increase temperature readings (decrease in relative humidity). This also affected the overall behaviour of the electrochemical sensors, which were subjected to high temperature transients whenever radiation conditions varied. This issue was addressed by the overall reduction of the LLS body, and the inclusion of a thermoformed plastic cover as shown in Figure 20. To obtain reliable temperature readings, an external temperature probe was added as seen in Figure 19.

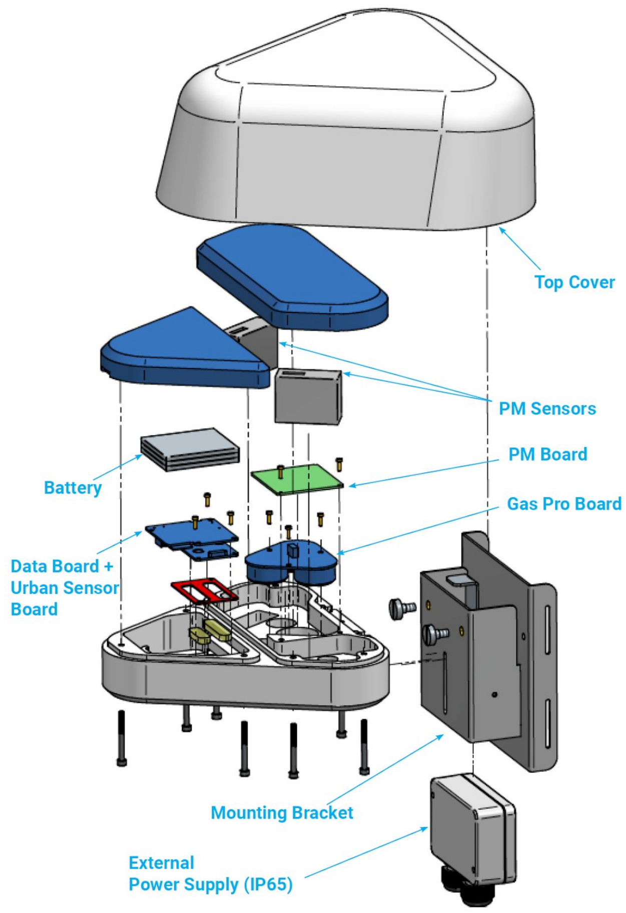


Figure 20. Living lab station exploded view

Access to the SD-card and to the data board within the station was too complex. This issue was addressed with a full redesign of the body of the station, which, as seen in Figure 22, was divided into two main areas for better usability.

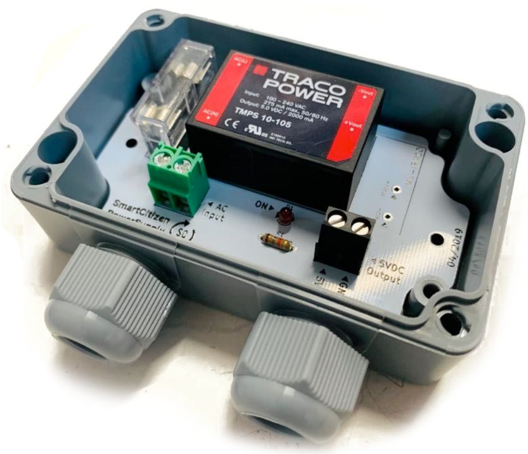


Figure 21. Custom power supply solution

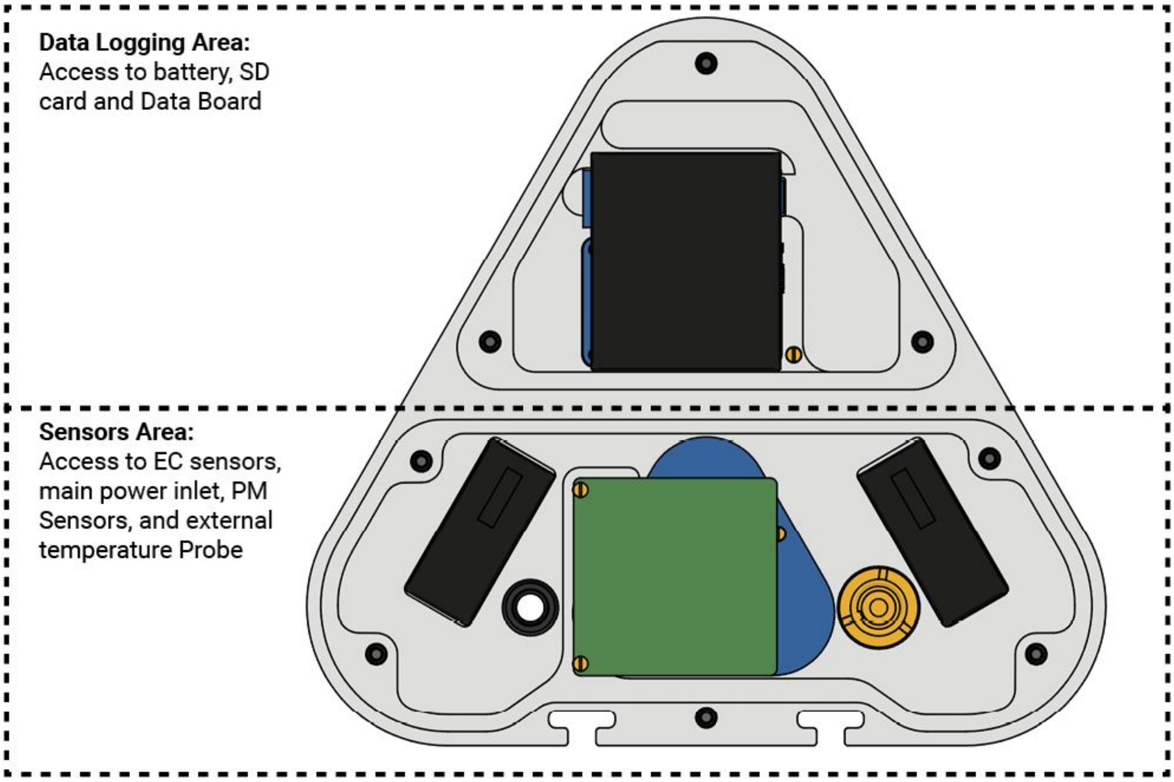


Figure 22. Area division for Living Lab Station

Figure 23 depicts the latest iteration of the LLS deployed in Barcelona, and the final list of sensors is shown in Table 9.

Sensor	Environment	Type	Application	Data post-processing
Sensirion SHT31	Indoor/Outdoor	Environmental	Temperature and relative humidity	Correction
Invensense ICS-434342	Indoor/Outdoor	Noise pollution	Noise Level and FFT Spectrum	Special
Rohm BH1721FVC	Indoor/Outdoor	Environmental	Ambient Light (directional)	None
NXP MPL3115A26	Indoor/Outdoor	Environmental	Barometric pressure, AMSL	None

AMS CCS811	Indoor	Chemical composition	eCO2 and TVOC	Correction
2 x PMS 5003	Indoor/Outdoor	Particulate Matter	Particulate Matter (external)	Correction
Alphasense CO-B4	Outdoor	Chemical composition	CO	Calibration
Alphasense NO2-B43F	Outdoor	Chemical composition	NO_2	Calibration
Alphasense OX-B431	Outdoor	Chemical composition	OX (O_3+NO_2)	Calibration
DS18B20	Indoor/Outdoor	Environmental	Air temperature	Correction

Table 9. Living Lab Station list of sensors

Figure 23. LLS final iteration in action

The units for deployment of this final iteration of the LLS are in the process of fabrication and deployment in the final month of the iSCAPE project and therefore no actual deployment data is currently available. Results for the available deployments of the LLS are shown in the following chapter.

In addition to the deployment locations mentioned in Table 7, one LLS was deployed in Barcelona, as part of the evaluation of the last iteration of the LLS. Additionally, three LLS are planned to be deployed in the Alphasense Ltd testing facilities in Braintree (England), as well as the Urban Traffic monitoring station in the neighbourhood of Eixample in Barcelona.

6. From measurements to results

Special effort were needed to create a reliable and usable data post-processing framework for sensor metrics. Initially to be used with the iSCAPE set of sensors, the tools developed are aimed at being exploited by others wanting to analyse sensors in the broad sense. For example the CS workshop data analysis was conducted using tools from this framework, downloading data from the Smart Citizen API, extracting metrics and performing data cleaning. In this chapter, an introduction of the overall approach for data analysis is detailed, going further into the analysis of the test conducted in the different iSCAPE sites.

6.1 Data processing description

Two main groups of sensors are considered when discussing their data processing. From the sensors shown in Table 9, the two groups are distributed as follows:

- **Sensors that require data correction.** These sensors already provide an off-the-shelf result, but this can be affected by the normal operation of the SCK. In this group, sensors such as temperature, humidity, and PM are included.
- **Sensors that require calibration.** These sensors do not output a usable processed value in understandable units, being the values that can be retrieved from them considered as *raw data* (i.e.: electrode readings in mV from electrochemical sensors). The Alphasense electrochemical sensors are part of this group. CO2 (and TVOC), is not considered to be part of this group, since the sensor already includes an internal temperature and humidity compensation by the manufacturer, with its own algorithm implementation. More details about this can be found in the manufacturer's **datasheet[36].**
- **Sensors that do not require any data processing.** In this group, sensors such as the light or barometric pressure are included, and no calculation is performed.

The microphone is considered to be a special case, in which the raw data is passed through a FFT algorithm in order to extract its frequency spectrum. This is part of the normal processing sequence for signal processing for microphones, which aims to extract a Sound Pressure Level (SPL) in the dB (deciBel scale) by calculating the RMS (root mean square) of this signal.

[36] https://ams.com/ccs811#tab/documents

In order to represent different sound perception cases by humans, often a weighting correction on the frequency spectrum is applied, to later obtain the RMS value with this corrected value (A, C or Z scales). Furthermore, since the microphone can have different responses to different frequencies, a correction can be applied, in the so-called equalisation process. The microphone has been validated in an anechoic chamber, in order to assess its performance and calibrate its frequency response. The tests were conducted in the Laboratory of Acoustics at the University of La Salle, Barcelona, during the month of July 2017. During these tests, a double point comparison between the reference microphone and the TDK ICS43432 was carried out and its results are shown in Figure 24. For reference, the upper and lower tolerances are extracted from the IEC 61672-1 Standard[37], although there is no particular aim to achieve these targets. In addition, a white noise characterization was performed to assess the frequency spectrum of the microphone that is mounted. This frequency spectrum is shown in Figure 25 and is used to equalize the frequency response (note the spectrum is independent of the SPL as shown in the figure). The area between 5000 and 7000Hz is not considered for the equalization, as it is not shown in the ICS43432 datasheet, and it is considered an experimental error or a particular resonance of the PCB:

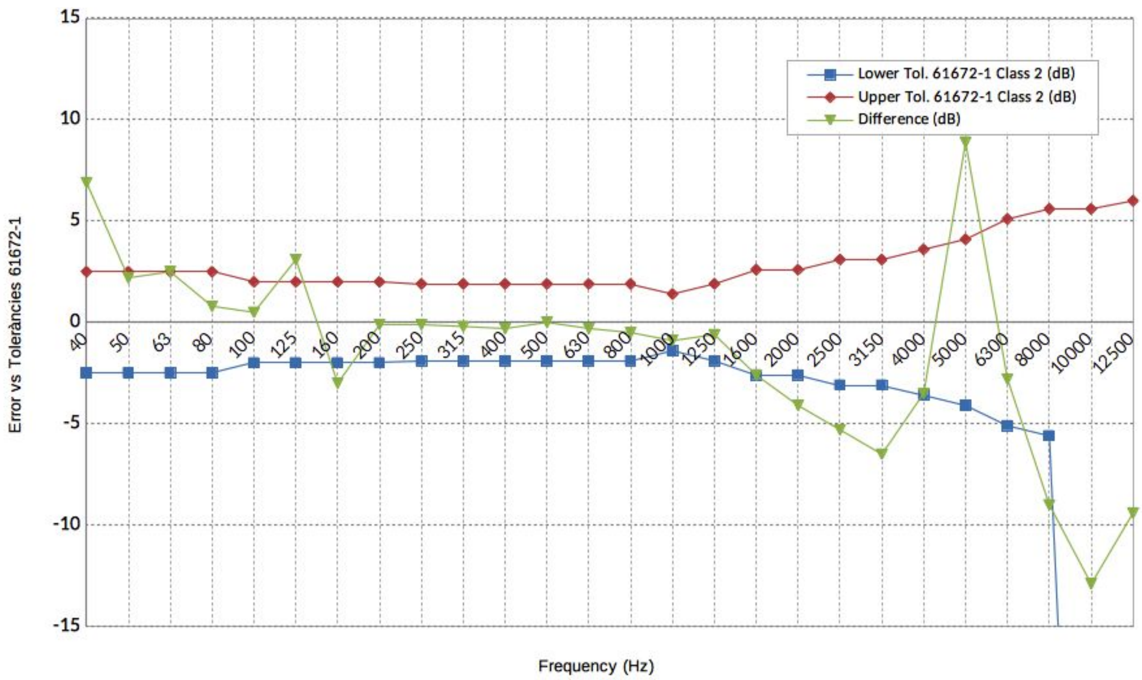


Figure 24. Double point comparison (no equalisation)

[37] IEC 61672-1 Standard Electroacoustics Sound level meters.
url: https://standards.globalspec.com/std/1634276/IEC%2061672-1

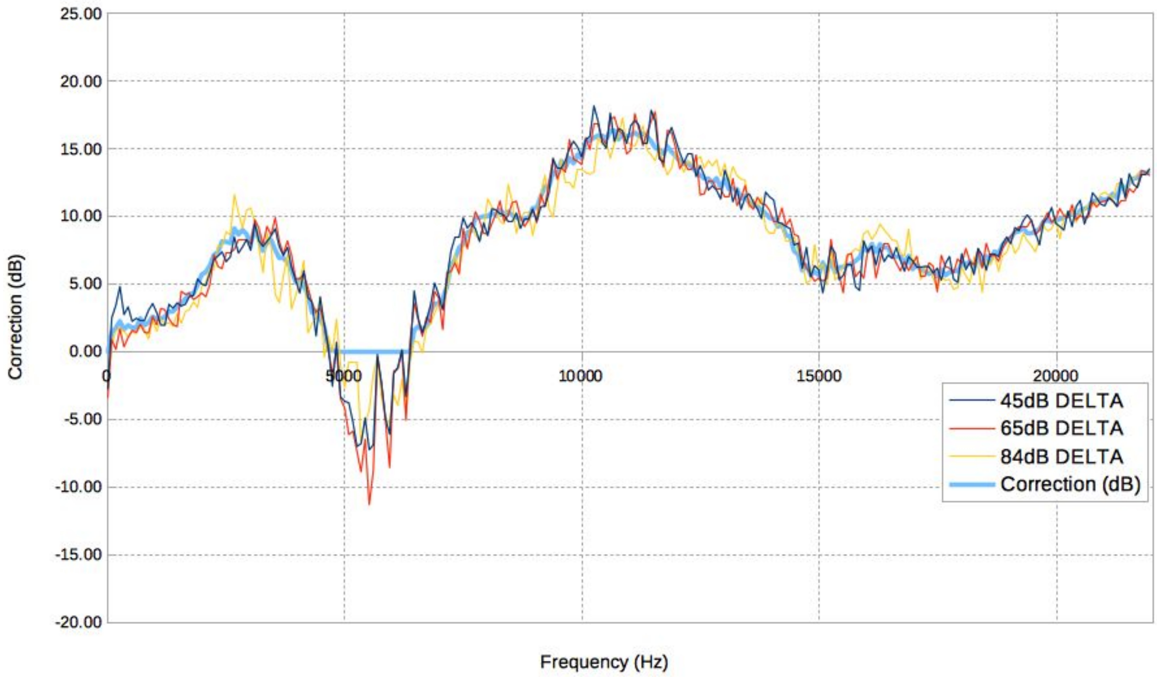


Figure 25. Spectrum equalisation

6.1.1 Sensors with correction

Temperature and humidity readings are corrected by an internal algorithm that aims to determine the offset in both measurements caused by the normal operation of the hardware. This improvement was part of the feedback detailed in section 5.1, and was implemented initially as a static offset depending on the mode of operation. Further firmware improvements then included a dynamic correction, which minimised the offsets described above.

In the case of the Particulate Matter sensors, a characterisation (Kuula et al. (2019) [15]) of several models of low-cost particle sensors including the PMS5003 was carried out as part of the collaboration activities with the Finnish Meteorological Institute (FMI, also iSCAPE partner). This characterisation included the PMS5003 and suggested that the sensor should not be calibrated by complex statistical models on the field, since it may yield misleading results. This study also found that the sensor response is best when measuring PM1, the PM2.5 detection values are highly dependent on the ratio of particle sizes distribution in that range. For this reason, a simpler approach for the PM sensor was explored, aiming to implement humidity correction based on particle's hygroscopicity as suggested by Di Antonio et al (2018) [16], but no further correction is applied for these sensors.

In the *Future opportunities* section below, other sensors are considered for the improvement of these metrics, but were not deployed within the iSCAPE project in urban environments.

6.1.2 Sensors with calibration

Sensors that require calibration can be approached in two different ways. These range from simple characterisation techniques based on manufacturer data and physical models (i.e. classical linear regression using sensor sensitivity, span and zero), or more advanced techniques, relying on statistical modeling. Physical modeling implies a big development effort in order to characterise the sensor behaviour that, in the case of low-cost sensors, is affected by a wide variety of external factors such as temperature, humidity and pollutant cross-sensitivity, each of which imply a larger characterisation effort and that can't be fully represented in a controlled setting. On the other hand, statistical models are able to generate models that describe the sensor behaviour in a mathematical way, but they need to be properly adjusted with large amounts of test data, preferably in the actual deployment site. This approach can be applied per sensor, or to a batch of sensors, assuming that the inter-sensor variation is low or that they can be normalised.

In the case of deploying the sensors in different locations, the conditions of these sites should be sufficiently similar to those when the model was generated, since many models won't be able to extrapolate well, or account for effects they have not seen (i.e. temperature gradients, specific pollutants, etc). How much is *sufficiently similar*, depends on the type of model and it is not easy to determine and, since this is not often assessed easily, researchers suggest (Kizel et al. (2017) [17], Dušan et al. (2018) [18]) that a co-location prior to and post data acquisition with reference sensors should be carried out. In any case, the development of these models highly depends on the amount and quality of the data obtained from both: sensor data and reference data. In the case of reference data, Dušan et al. (2018)[18] have pointed out that reference stations can deviate up to 15% from the actual pollutant concentration, but this has not been taken into account in this study.

Since co-location possibilities could be limited for end researchers, two options are compared for the calibration of these sensors within the scope of the iSCAPE Project: a specific on-site calibration with sensor co-location, aiming to calibrate the sensors with the data from that period (Figure 26 right); and a general model approach (Figure 26 left), in which all the co-location tests from the different sensors deployed are input into a statistical model that aims to describe the global behaviour.

In the case of the first approach, the minimum amount of data required for a proper sensor calibration is also studied, as well as the possibility of extrapolating the results to nearby sensors (after normalisation).

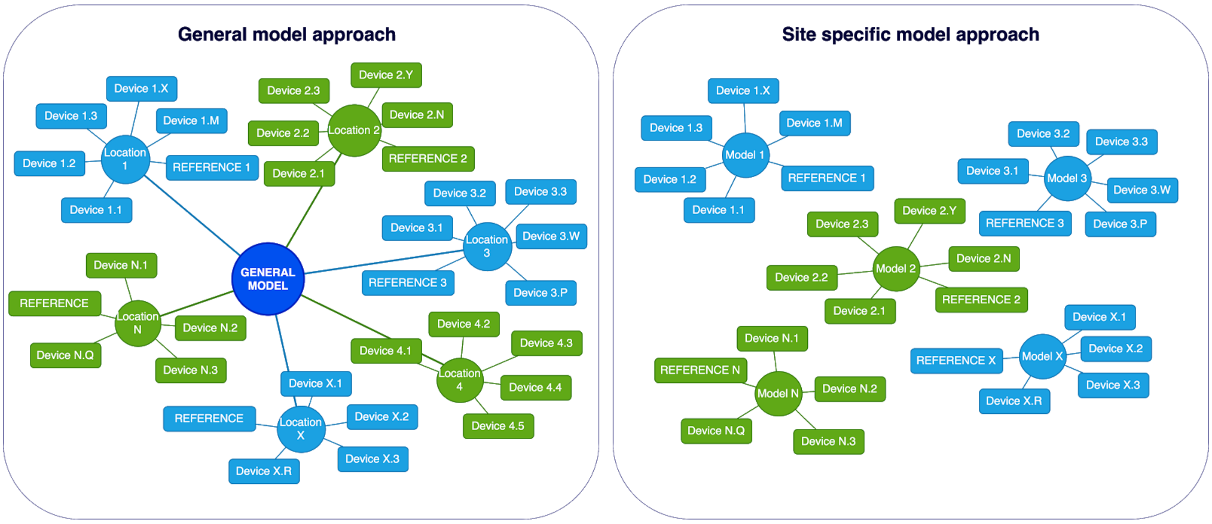


Figure 26. Model approaches

In the case of the general model approach, the main advantage is that not all the locations are in need of a reference station for estimating actual pollutant concentrations. However, since the locations can differ significantly, the general model needs a sufficient amount of data input for being able to represent reliably a location in which no high end sensor is present. How much this amount of data would be is unknown, and it is also analysed in this study. To summarise, this study aims to determine:

- **The amount of time** needed to co-locate the sensors with reference stations for both approaches.
- If the sensors should be **co-located prior and post deployment**.
- If the **sensor calibration from one site can be used for other sites** (extrapolation and normalisation), hence if a generic model approach is valid.

Alphasense electrochemical sensors are toxic gas sensors that operate in an amperometric mode. That is, they generate a current that is in theory linearly proportional to the fractional volume of the toxic gas in the environment. These electrochemical sensors are comprised of four electrodes: working, auxiliary, counter and reference electrodes. The working electrode is where the oxidation (CO, H_2S, NO, SO_2) or reduction (NO_2, Cl_2) of the toxic gas to be measured takes place. This electrode is exposed to the outside air and directly exposed to all gases in the air including the gas to be measured. The auxiliary electrode is an electrode of the same characteristics to those of the working electrode, but it is buried inside the electrolyte and, hence it is not in contact with the target gas. Since it is isolated from external conditions that could affect the working electrode, it serves as a reference to the raw measurements. The other two electrodes are not used in the pollutant calculation, but are necessary for the sensor operation. Finally, the manufacturer provides with sensitivity (ppm/nA) and zero current data (nA) for each of the sensors, which can be used for normalisation. Given these circumstances and iSCAPE project timeline, two stages were followed in the development of a post-processing approach for these sensors:

- Literature review and implementation of physical models based on manufacturer's data. The model selected was developed by Popoola et al. (2016) [8] and uses a Baseline estimation algorithm to subtract temperature or humidity effects from the sensor data. In the case of the study by Popoola et al, the sensors that the authors used were the 3-electrode version. In the iSCAPE project hardware, the 4-electrode version was selected, (B-series[38]), since the manufacturer claims a better stability for these sensors due to the larger amount of electrolyte. The model developed for the iSCAPE project is based on the above mentioned study by Popoola et al. but uses the data from the additional electrode (auxiliary electrode) to compensate for temperature and humidity effects. More details of the actual implementation and results can be found in the official Smart Citizen documentation[39], and the code can be found in the sensors analysis framework source code[40].
- Testing and application of statistical models. Sensor deployment on site and co-location with high-end sensors was carried out as part of the sensor evaluation campaign mentioned in previous chapters, generally towards the end of the project. This campaign intended to evaluate test data from 12 sensors located in various iSCAPE partner locations, however not all the sites could deploy these reference sensors or perform co-location near official sites of the local government authority. From the sites listed in Table 7 that are tagged as *calibration* (a total of 6 stations) the only long term data available at the moment of writing this deliverable is from UCD (more than 1 month), although other sites such as the Vantaa Living Lab have planned activities with a larger amount of sensors. In addition, further testing is planned to be conducted as part of outreach activities detailed in the following chapter, in collaboration with the sensor manufacturer Alphasense Ltd and local authorities in Barcelona.

[38] Alphasense Air B-series products: http://www.alphasense.com/index.php/air/products/
[39] Documentation on electrochemical sensors calibration: https://docs.smartcitizen.me/Components/Gas%20Pro%20Sensor%20Board/Electrochemical%20Sensors/#sensor-calibration
[40] Sensors analysis framework source code: https://github.com/fablabbcn/smartcitizen-iscape-data

6.2 Performance assessment metrics

In this section, the metrics for the evaluation of the performance of each model are explained, as well as the summary diagram used for model comparison (Joliff et al. (2009) [19]). In all the definitions below, *m* indicated the model, and *r* indicates the reference. *Overbar* indicates average and *σ* the standard deviation.

- *Correlation coefficient (R)*: a common measure of the agreement of a model and its reference. Usually noted by, it can express if the relationship between both variables is linear or not, as well as its direction:

$$R = 1/N \frac{\sum_{n=1}^{N}(m_n-\overline{m})(r_n-\overline{r})}{\sigma_m \sigma_r}$$

- *Coefficient of determination* (R^2): expresses the agreement between the model and its reference, but contrary to R, it only can denote the magnitude of this agreement. It's bounded between ($-\infty < R^2 < 1$), being 1 the closest to a perfect agreement. If R^2 is below 0, the estimation made by the model is a worse estimator than the average from the reference. In the equation below, SS denotes the total sum of squares:

$$R^2 = 1 - SS_{reg}/SS_{tot}$$

$$SS_{reg} = \sum_{n=1}^{N}(m_i - \overline{r})^2$$

$$SS_{tot} = \sum_{n=1}^{N}(r_i - \overline{r})^2$$

- *Root mean square deviation (RMSD):* measures the differences between the values predicted by a model or an estimator and the values observed. The RMSD does not take into account the bias of the two signals

$$RMSD = \sqrt{\frac{SS_{reg}}{N}}$$

- *Bias (B)*: the difference between the means of the model and its reference:

$$B = \overline{m} - \overline{r}$$

- *Unbiased RMSD (RMSD')*: overall agreement between the amplitude (*σ*) and phase (*R*) of two temporal patterns.

$$RMSD' = \sqrt{1/N \sum_{n=1}^{N} [(m_n - \overline{m}) - (r_n - \overline{r})]^2}$$

$$RMSD'^2 = \sigma_r^2 + \sigma_m^2 - 2\sigma_r\sigma_m R$$

- *Normalised bias (B*)*: difference between two means normalised to the standard deviation of the reference

$$B^* = \frac{\overline{m} - \overline{r}}{\sigma_r}$$

- *Normalised standard deviation (σ*)*:

$$\sigma^* = \sigma_m / \sigma_r$$

- *Normalised unbiased RMSD (RMSD'*)*: a measurement of the temporal agreement of the model and its reference, normalised to the standard deviation of the reference (RMSD'*):

$$RMSD'^* = \sqrt{1 + \sigma^{*2} - 2\sigma^* R}$$

Finally, the target diagram described in Joliff et al. (2009) [19] is used for model performance comparison. The diagram represents the normalised bias (B*) versus the normalised unbiased RMSD (RMSD'*). This representation provides information about whether the model standard deviation is larger (X>0) or smaller (X<0) than the reference standard deviation. In addition, it provides information about the positive (Y>0) and negative (Y<0) bias. In addition, the distance to the center is related with R^2, and then serves as a useful comparison for the models' ability to represent the pattern of the signal.

6.3 Results

In this section, results from the different deployments are discussed. Results are divided into two groups: intervention monitoring tests and calibration tests. Before diving into the results, an important fact to highlight is the evolution of the data reliability that the sensors have been able to achieve during these deployments. Figure 27 represents the evolution of the data validity ratio (as a percentage of the total deployed days) for all the sites that carried out deployments with the LLS, as well as the total amount of days that the sensors were operating. In Figure 27, after the device named as *5261*, all LLS are based on the SCK2.0, which allowed for an increase on the data validity ratio, although sensors 5261, 5262 and 5565 were the first sensors built for this version and some iterations still applied. Sensors with lower data validity ratios (amount of valid data vs. total amount of days deployed), as the devices 5527, 5262 or 5565, showed problems with the PM sensors and or the power supply, which implied a recall of the sensor for repair. These issues were solved rapidly to continue with the deployment of the devices, and re-designed for better stability in the next iteration of the LLS.

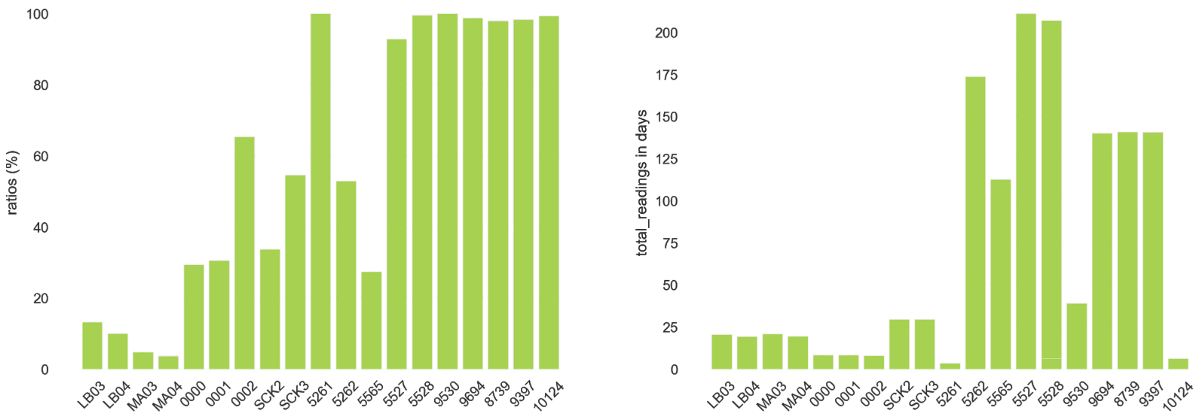


Figure 27. Ratio of data usability and total readings in days

6.3.1 Intervention monitoring results

Two intervention monitoring results were conducted in the sites of Surrey (UoS) Living Lab and Hasselt (UH) Living Lab. A summary of the dates and number of stations for these tests is shown in Table 10.

Location	Station type	Test Type	Number of stations	Dates
Surrey	SCK2.0	Intervention monitoring	2	12th Feb 2019 to date
	SCK2.0	Intervention monitoring	2	6th Jun 2019 to date
Hasselt	SCK2.0	Conditions assessment	2	19th Jun 2019 to date*

Table 10. Surrey and Hasselt deployment dates

The intervention in Surrey aimed at characterising the behaviour of green infrastructure and the effect on the pollutants dispersion next to traffic conditions. Two different sets of two stations were delivered and deployed, one set in the vicinity of Stoke Park, and the other in the vicinity of Sutherland Memorial Park (both in Guildford - UK). In both locations, the tests were conducted with one station behind the hedge and one next to the road, in order to assess the behaviour of the hedge throughout its different stations (flowering, greening, fall, etc). The data validity ratios for these deployments were high, in all cases larger than 90%, with a total amount of data of 200 days for the first set, and 100 days for the second set (deployed four months later).

In the case of Hasselt, two Living Lab Stations were deployed. The first one was used to assess pollutant concentrations in the *Bassischool Kuringen* in Hasselt. The other station was deployed near the University of Hasselt, but had only one month of valid data due to an issue not related with the Living Lab Stations itself, while the one in Kuringen School has been recording data for 140 days at the moment of writing this deliverable.

6.3.2 Calibration results for Bologna, UCD and Barcelona

The tests conducted in Bologna (by UNIBO, 2018), Dublin (by UCD, 2019) and Barcelona (by IAAC, 2019) were intended as an assessment of the sensor technology in an outdoor environment scenario, by co-locating the iSCAPE LLSs with reference instrumentation. These tests were conducted during the dates indicated in Table 11.

Location	Station type	Test Type	Number of stations	Dates
Bologna	SCK1.5	Co-location with ARPAE[41] reference	2	23rd Jan to 13th Feb 2018
	SCK2.0	Co-location with mobile unit - CO, NO2, NO	2	9th to 29st Aug 2018
	SCK2.0	Photocatalytic wall assessment	2	1st to 27th Sept 2018
Dublin	SCK1.5	Co-location with reference	2	Apr 2018
	SCK2.0	Urban Background	2	11th Jan to

[41] Regional Agency for Prevention, Environment and Energy of Emilia-Romagna - Italy

		(Dublin City Council) - CO, NO2, PM10 (daily avg)		23 Apr 2019
	SCK2.0	Urban Traffic (Blanchardstown)	2	22nd May to date
Barcelona	SCK2.1	CSIC monitoring station - Urban Background (CO, NO2, PM10)	1	16 May to 21st Jun 2019

Table 11. Summary of locations and dates for Dublin and Bologna sites co-location tests

In the case of the Bologna site, the first testing iteration during the beginning of 2018 did not yield significant data reliability, as the hardware and firmware was not mature enough for this type of deployments (see Figure 27, devices LB04 and MA04). The tests during August 2018 consisted of the installation of two LLS, each of them in different locations (Figure 27, devices SCK2 and SCK3, Figure 28 shows them in action). One station was located in a street canyon treated with photocatalytic coating and the other in a canyon without this treatment. During the month of August 2018, each LLS was co-located with a mobile measurement unit, with CO, O_3, NO_2, NO and NO_x as reference measurements. After this period, the mobile units were no longer available, and the LLS were located on the street canyons walls until the end of the month of September. The total amount of data collected for these two LLS was approximately 30 days of data, with 9 and 16 days of co-located reference data for each of the devices.

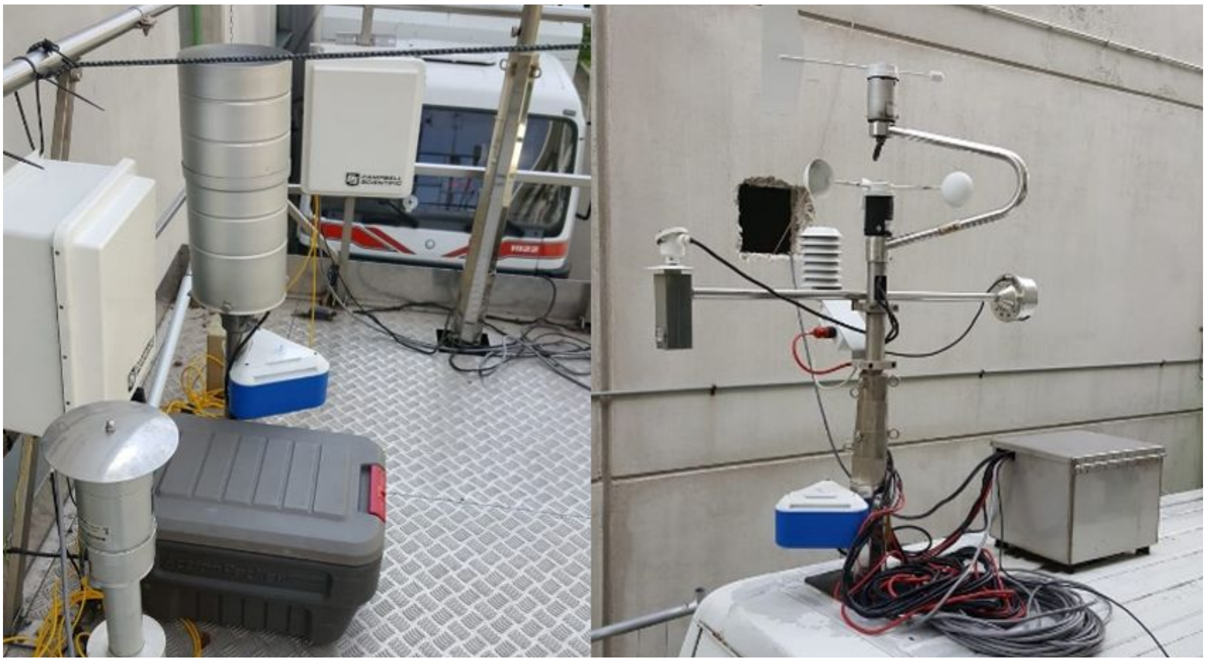


Figure 28. Lazzaretto site deployment - Aug-Sept 2018 - Bologna, Italy

In the case of Dublin's Living Lab site, the sensors were deployed in two locations, aiming to assess sensor behaviour in Urban Background conditions and Urban Traffic. The first site was Dublin's City Council (DCC), in a co-location of both LLS with reference equipment from the local authority. The second site was in the vicinity of the M50, in Blanchardstown. The stations were co-located in the site between the 1st of November 2018 to April 2019 at DCC, as shown in Figure 29, with a total amount of valid data of approximately 90 days, due to sensor issues with their power supply.

Figure 29. Dublin City Council Living Lab Stations

The tests from Barcelona were conducted in the urban background station in Palau Reial, for a total duration of approximately one month. Figure 30 shows the deployment of the device. The device was performing during the whole period with no data loss, and the results are discussed below.

Figure 30. Barcelona Station Deployment

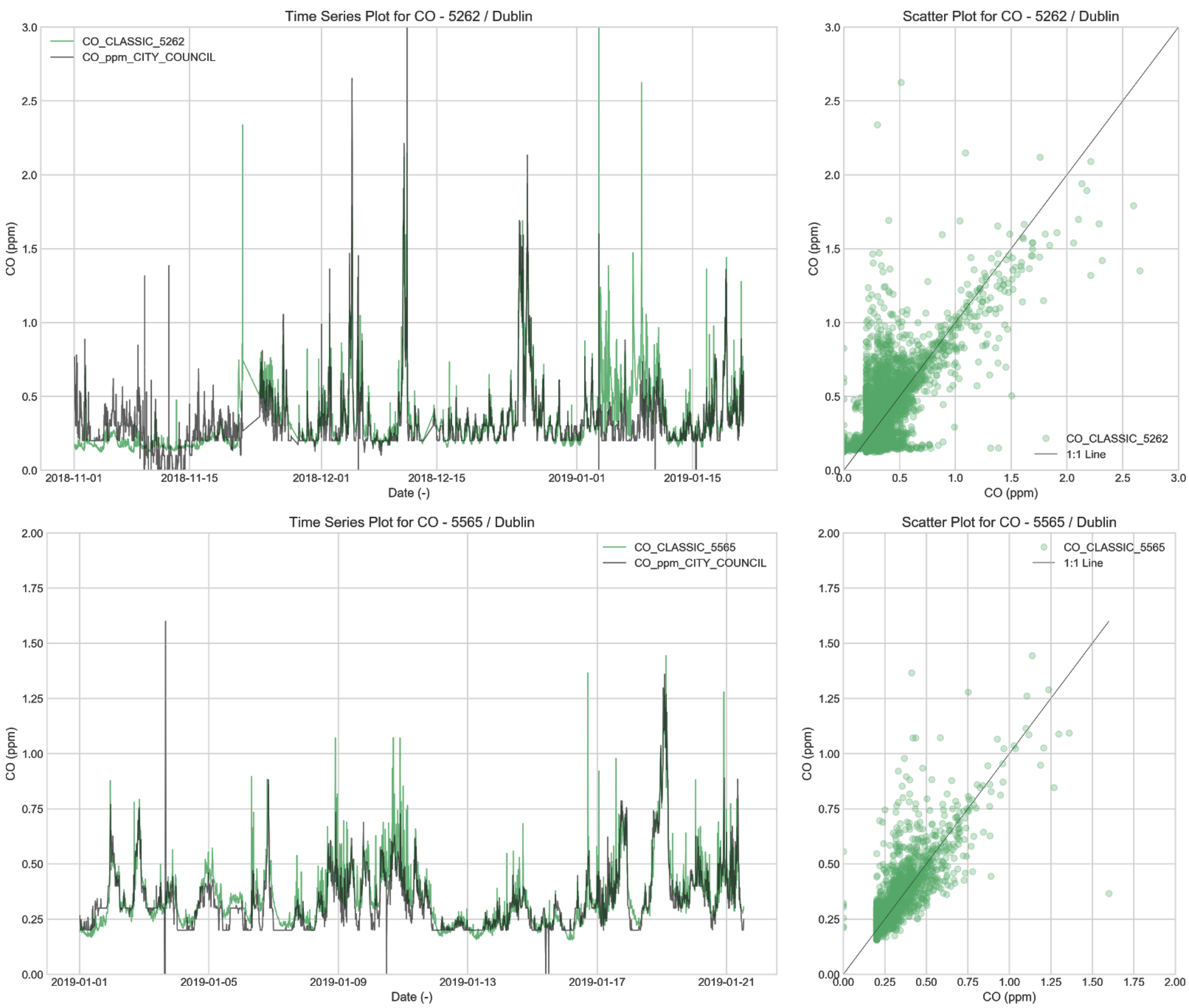
6.4 Discussion

Both Bologna and Dublin site tests were able to give an initial overview of the sensor data validity of the LLS. The tests in Bologna site had a lower validity ratio due to lower hardware and firmware stability. Tests in Bologna and Barcelona were carried out with higher average temperatures compared to those of the Dublin site (30ºC vs 15ºC), and with higher temperature gradients due to sunlight exposure changes. This will be discussed in the following paragraphs. The pollutants available for each of the locations are detailed in Table 11. None of the locations had O_3 available, and for this reason it is left out of this analysis until further data can be collected.

As mentioned above, two stages for data post-processing for the electrochemical sensors were followed: a physical model implementation, based on manufacturer's data; and a more advanced analysis using statistical models, based on data collected from various deployments. Both analysis are detailed z below.

6.4.1 Physical models

The comparison between the CO estimations from this physical model shows a very good correlation in all sites (average $R^2 > 0.5$). On the other hand, the NO2 models don't seem to correlate as well (R^2~0.2) and for this reason, statistical models are explored further. In Figure 31, results from the different sites and devices are shown for CO. Table 12. summarises the metrics extracted from this pollutant. The bias observed between the reference stations and the results in the sites of Bologna and Barcelona, are probably due to the larger temperatures found in those sites, which are said to affect the sensors sensitivity according to the manufacturer, although no evidence can prove this with the data available from this study. Note that the results from Barcelona have very small temporal resolution and the reference minimum measurement is 0.25ppm, therefore showing a meaningless R^2. It is also important to note that the temporal agreement of the signals in the shape of R^2 is conditioned by the sampling of the signals, in which no averaging was performed.



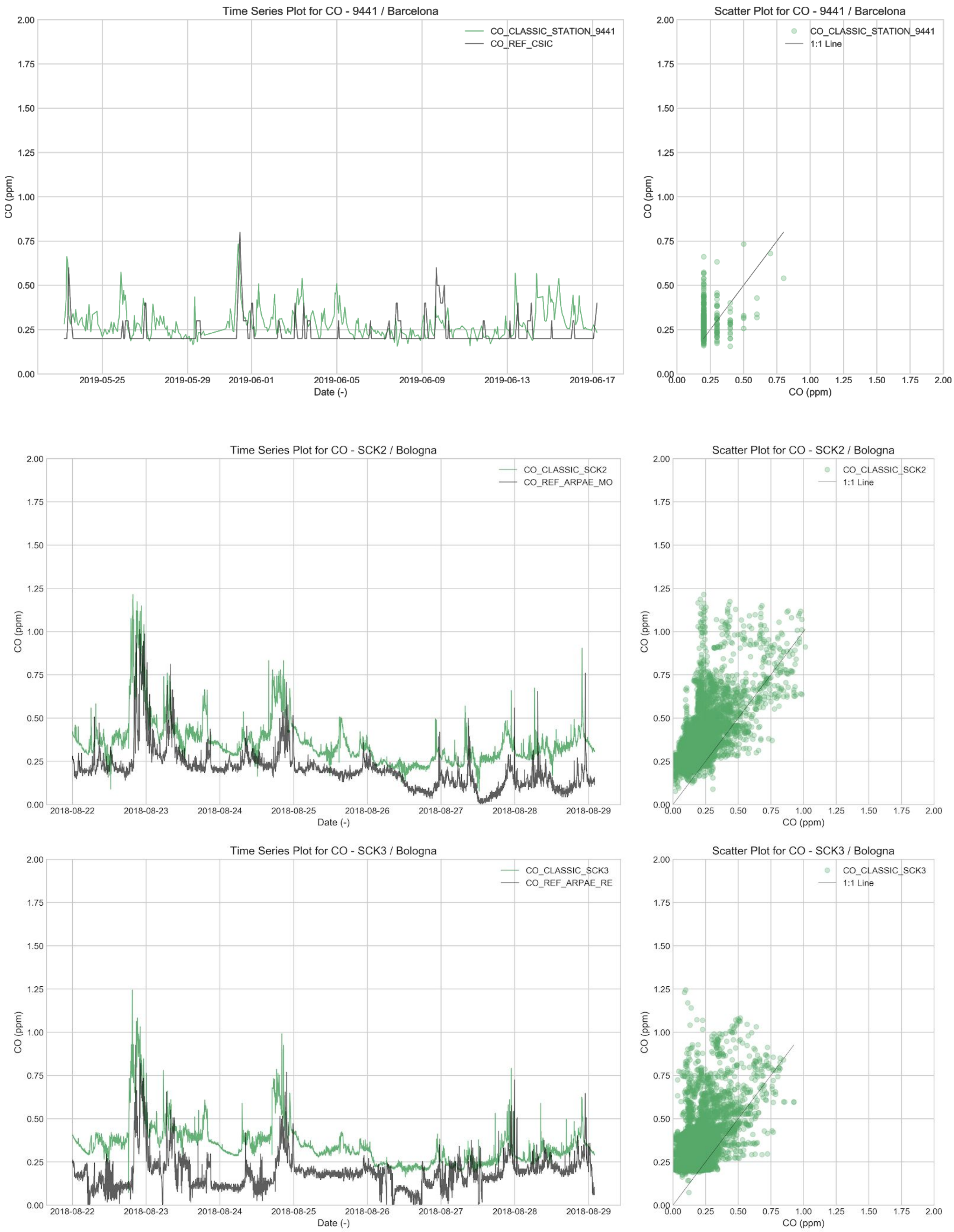


Figure 31. Results of CO calculation with physical models in different sites

City / Location	Device name	R^2	RMSD (ppm)
Bologna / Lazzaretto	SCK2	0.4	0.2
	SCK3	0.3	0.2
Dublin / DCC	5262	0.5	0.2
	5565	0.6	0.1
Dublin / Blanchardstown	5262	na	na
	5565	na	na
Barcelona / Palau Reial	9941	na	0.1

Table 12. Summary of CO calculation metrics with physical models in different sites

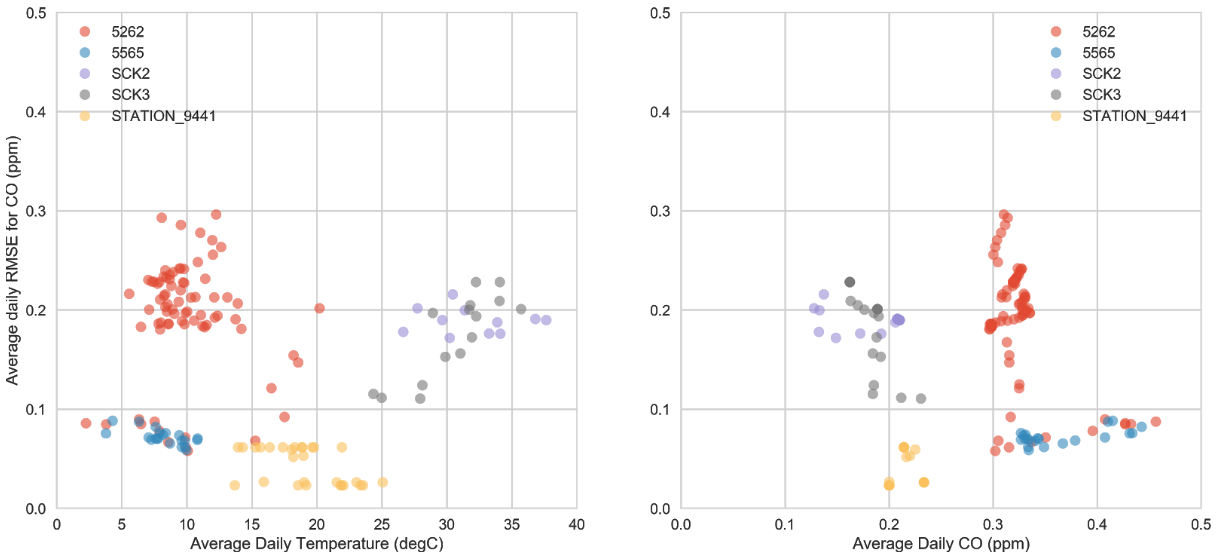


Figure 32. Average daily Root Mean Square Error for CO with respect to average daily temperature and CO

Figure 32 shows the average daily RMSE for the CO models with respect to the average daily temperatures and CO actual concentrations. The plot with respect to the temperature shows what the RMSE does not depend on this factor significantly, although this is stated in the technical specification from the sensor manufacturer. The RMSE does not depend either on the pollutant concentration, and seems to be more related to an actual miss-characterisation of the sensor sensitivity, since the points are generally clustered by sensor.

The results for NO_2 are highly dependent on the pollutant concentration. This is due to the sensors don't seem to react in the same linear fashion with concentrations below 20 ppb of NO_2, and it is possible that there is an overlapping effect of the temperature, reducing the sensor's sensitivity. The results for the NO_2 measurements for the in Dublin and Barcelona sites are shown in Table 13, Figure 33 and 34 highlight a focus in a period where low and high concentrations are combined. During this last period, the average R^2 shown in Table 12 improves to 0.4. Nevertheless, this approach does not seem to be able to capture the variance and the model fails to represent pollutant concentrations below 20 ppb.

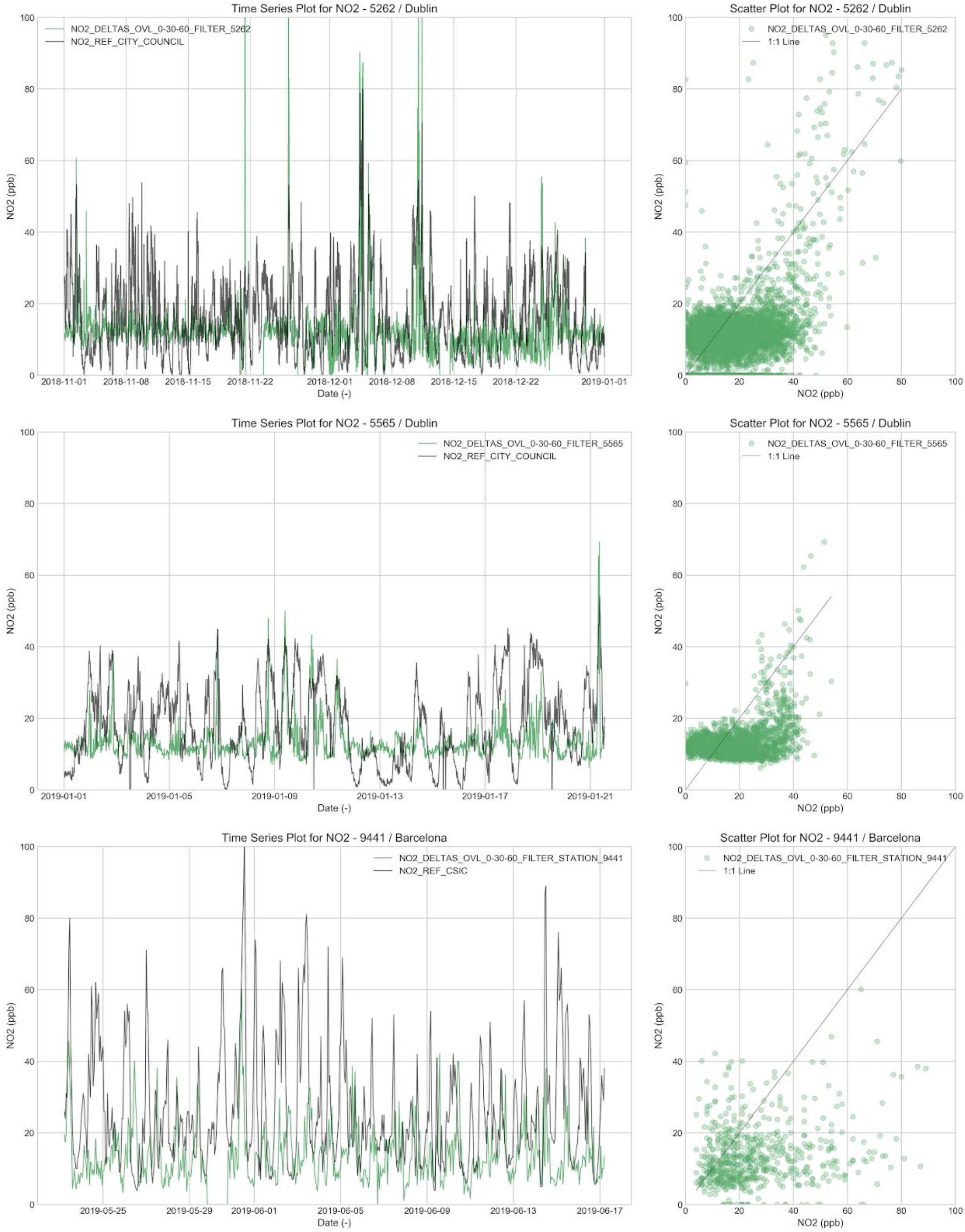


Figure 33. Results of NO2 calculation with physical models in different sites

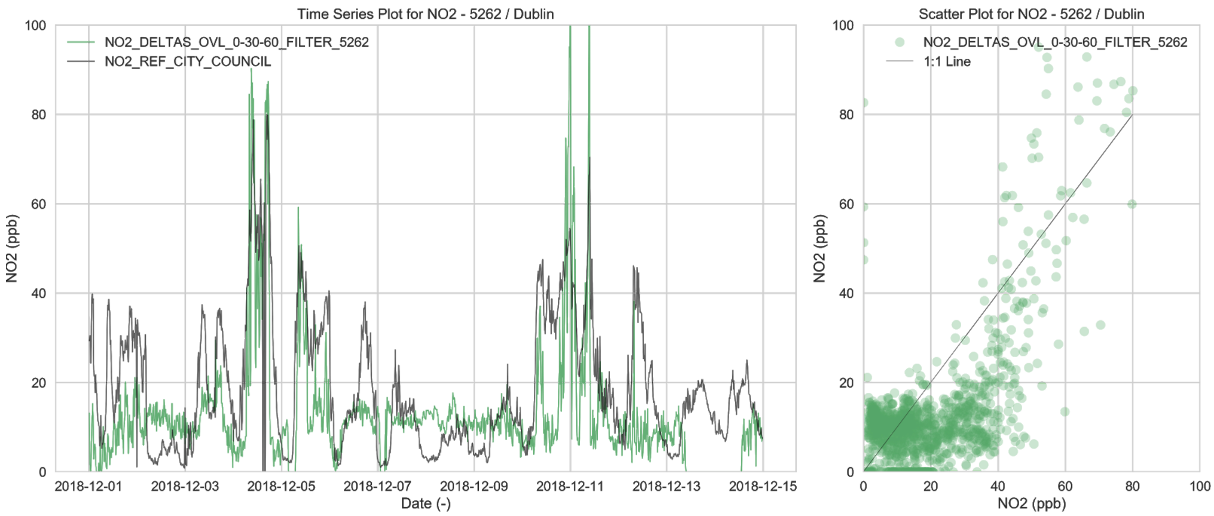


Figure 34. Focus on two weeks of NO2 calculation with physical models in Dublin DCC

In the case of Bologna, the NO_2 electrochemical sensors were highly affected by temperature transients. These temperature gradients provoked instabilities in the electrochemical sensors, as shown in Figure 35, that need to be accounted for in possible model corrections, as suggested by Hagan et al. (2018) [9].

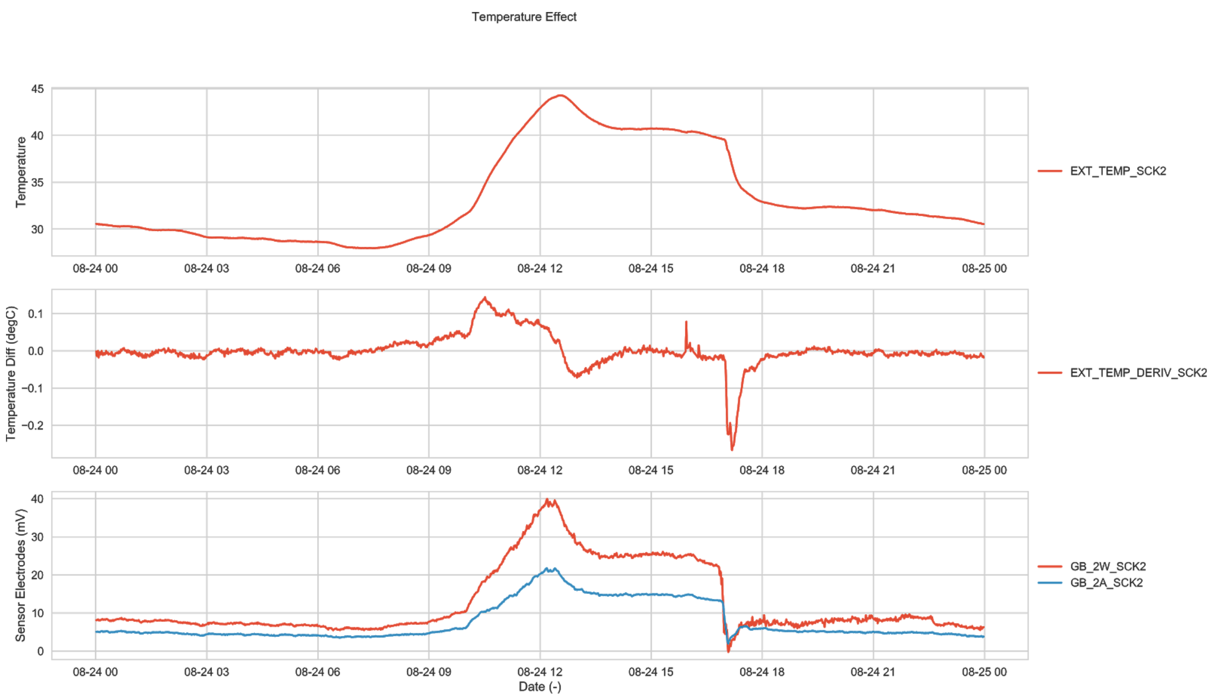


Figure 35. Temperature instability effects on EC sensor measurements

City / Location	Device name	R^2	RMSD (ppb)
Dublin / DCC	5262	0.15	12
	5565	0.15	11
Dublin / Blanchardstown	5262	na	na
	5565	na	na
Barcelona / Palau Reial	9941	na	0.1

Table 13. Summary of NO2 calculation metrics with physical models in different sites

Figure 36 shows the relationship between R^2 and RMSE for NO_2 with respect to the actual pollutant concentration. The negative values of R^2 indicates that the estimation is worse than the average of the reference, and this begins to occur roughly at 20-25 ppb NO_2. This indicates that for the low concentration areas further development effort is necessary.

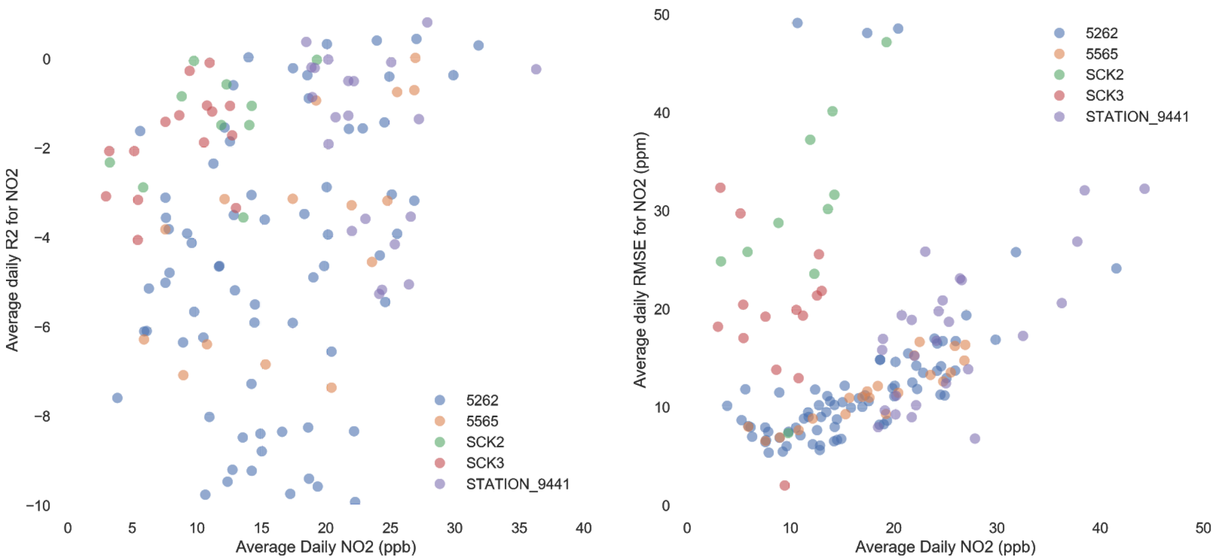


Figure 36 R^2 and RMSE for NO_2 with respect to the actual pollutant concentration

6.4.2 Statistical models

Models for electrochemical sensors can be developed based on previous results using more advanced modeling techniques. This derived on the experience during these deployments and the literature available, different types of models are tested, ranging from OLS (ordinary least squares) and RLM (Robust Linear Models), and more advanced machine learning methods such as random forest techniques (RF) and gradient boosting machines (GBM).

Two scenarios are presented, based on the modeling approaches from Figure 27: generic model approach, and site specific model approach. Each method will be analysed separately, the models from the site specific approach will be evaluated on the devices tested on the other locations, aiming to test whether or not these models can generalise to devices in various locations. For simplicity, the only site specific model that will be evaluated with the rest of the devices will be the one with the longest available data (Dublin, device 5262). The generic model approach shown in Figure 26 will be evaluated for all the devices available, in all the locations.

6.4.2.1 Site specific models

Table 14 shows a comparison of the different models tested for the site specific approach, based on device 5262 from Dublin's DCC, for both pollutants. For each model type, the best combination of the models hyperparameters is shown. In this case, a model developed with 70% of the Dublin's device is developed, which results in 45 days of data out of 60.

Table 14 summarises an expected outcome: models that are calibrated with data from sensors, only apply to those same sensors, as no model type is able to perform better than the baseline model in other devices. The models extracted from the RLM and the RF seem to apply for the device co-located in the same site in Dublin's DCC, but only because the features used for the model are naturally normalised. This has not been discussed in previous reviewed publications and constitutes a major problem when developing models for air pollution calculations.

<table>
<tr><th rowspan="2">City/ Location</th><th rowspan="2">Device</th><th rowspan="2">Pollutant</th><th>Baseline Model</th><th colspan="2">Linear Model (RLM)</th><th colspan="2">Random Forest</th><th colspan="2">XGBoost</th></tr>
<tr><th colspan="7">R^2 / RMSD (ppm CO, ppb NO_2) - Train/test sets for model device</th></tr>
<tr><td rowspan="4">Bologna/ Lazzaretto</td><td rowspan="2">SCK2</td><td>CO</td><td>0.4 / 0.2</td><td colspan="2">na / 0.2</td><td colspan="2">0.1 / 0.1</td><td colspan="2">0.2 / 0.1</td></tr>
<tr><td>NO_2</td><td>na</td><td colspan="2">na / 14.4</td><td colspan="2">na / 12.5</td><td colspan="2">na / 10</td></tr>
<tr><td rowspan="2">SCK3</td><td>CO</td><td>0.3 / 0.2</td><td colspan="2">na / 0.5</td><td colspan="2">na / 0.16</td><td colspan="2">na / 0.16</td></tr>
<tr><td>NO_2</td><td>na</td><td colspan="2">na / na</td><td colspan="2">na / 12.1</td><td colspan="2">na / 15</td></tr>
<tr><td rowspan="4">Dublin/ DCC</td><td rowspan="2">5262 (model)</td><td>CO</td><td>0.5 / 0.2</td><td>0.6 / 0.15</td><td>0.9 / 0.1</td><td>0.97 / 0.04</td><td>0.9 / 0.08</td><td>0.8 / 0.1</td><td>0.87 / 0.1</td></tr>
<tr><td>NO_2</td><td>0.15 / 12</td><td>0.2 / 10.7</td><td>0.1 / 9.7</td><td>0.9 / 2.6</td><td>0.2 / 9.1</td><td>0.5 / 8</td><td>0.1 / 9.3</td></tr>
<tr><td rowspan="2">5565</td><td>CO</td><td>0.6 / 0.1</td><td colspan="2">0.7 / 0.1</td><td colspan="2">0.7 / 0.1</td><td colspan="2">0.5 / 0.1</td></tr>
<tr><td>NO_2</td><td>0.15 / 11</td><td colspan="2">0.15 / 10</td><td colspan="2">0.1 / 10.7</td><td colspan="2">na / 13</td></tr>
<tr><td rowspan="2">Barcelona/ Palau Reial</td><td rowspan="2">9941</td><td>CO</td><td>na / 0.1</td><td colspan="2">na / 0.1</td><td colspan="2">na / 0.1</td><td colspan="2">na / 0.1</td></tr>
<tr><td>NO_2</td><td>na / na</td><td colspan="2">na / 27</td><td colspan="2">na / 17.7</td><td colspan="2">na / 19</td></tr>
</table>

Table 14. Metrics summary for site specific models

Figure 37 shows the comparison between the CO from the linear and machine learning models in the modeled device. Figure 38 shows how this same model extrapolates to the other devices. In the case of the CO, the baseline model and the sensor metrics are sufficiently close to the target pollutant for the model to perform well. This comparison already shows two conclusions: the first one is about the performance of the machine learning model, which is able to capture better the characteristics of the signals and therefore outperforms the robust linear model.

Secondly, none of the models is to be applied in other devices other than the one that was used for the calibration, since it is not able to extrapolate properly. This is shown in Figure 38, where the machine learning model has not captured all the necessary conditions of the original device, although it is able to reduce the RMSD, while the linear model is able to extrapolate further, but with a limited performance. As shown in the next section, this can be improved by including more devices into the training dataset.

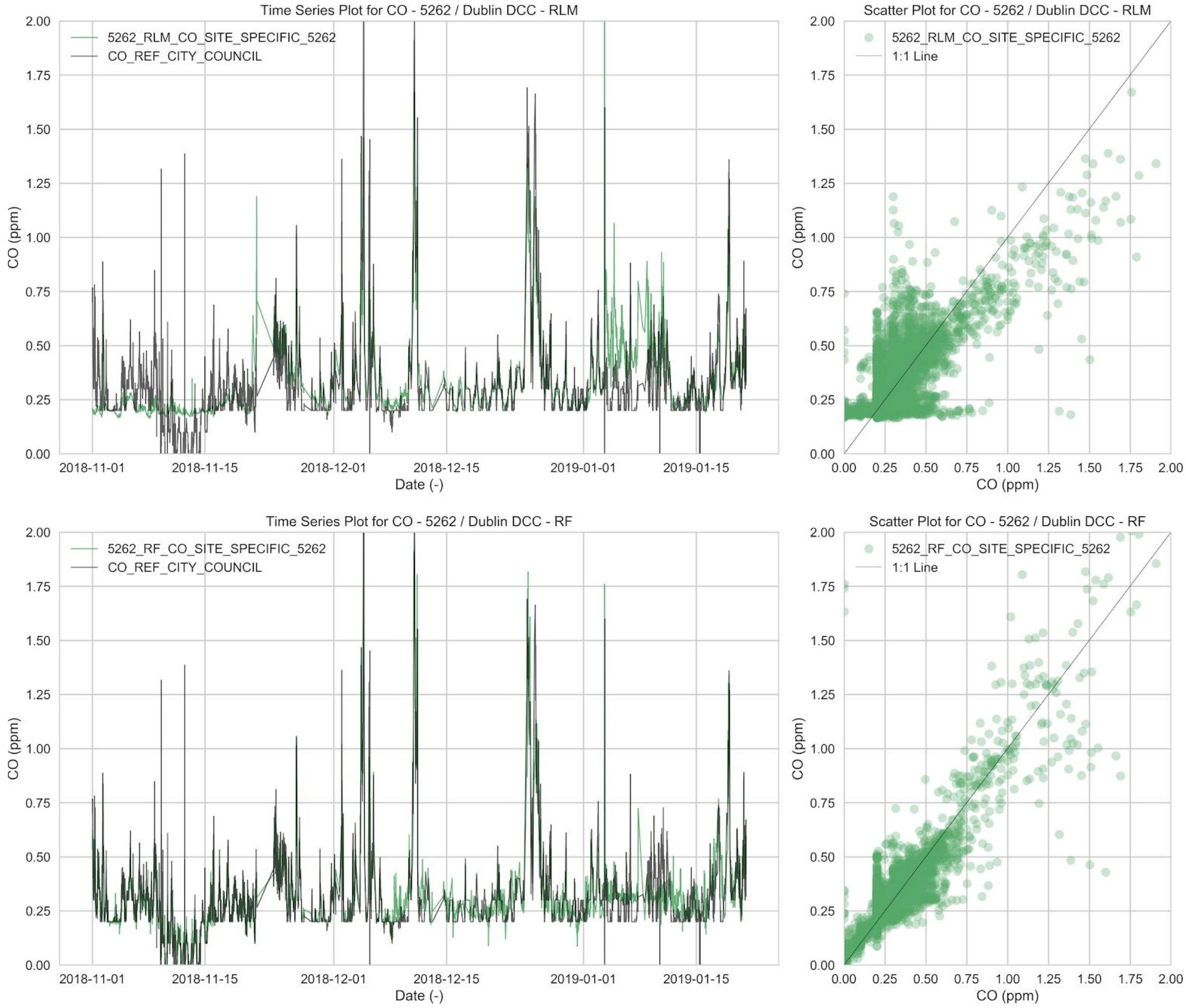


Figure 39. Comparison of CO between RLM and RF with site specific approach - 5262

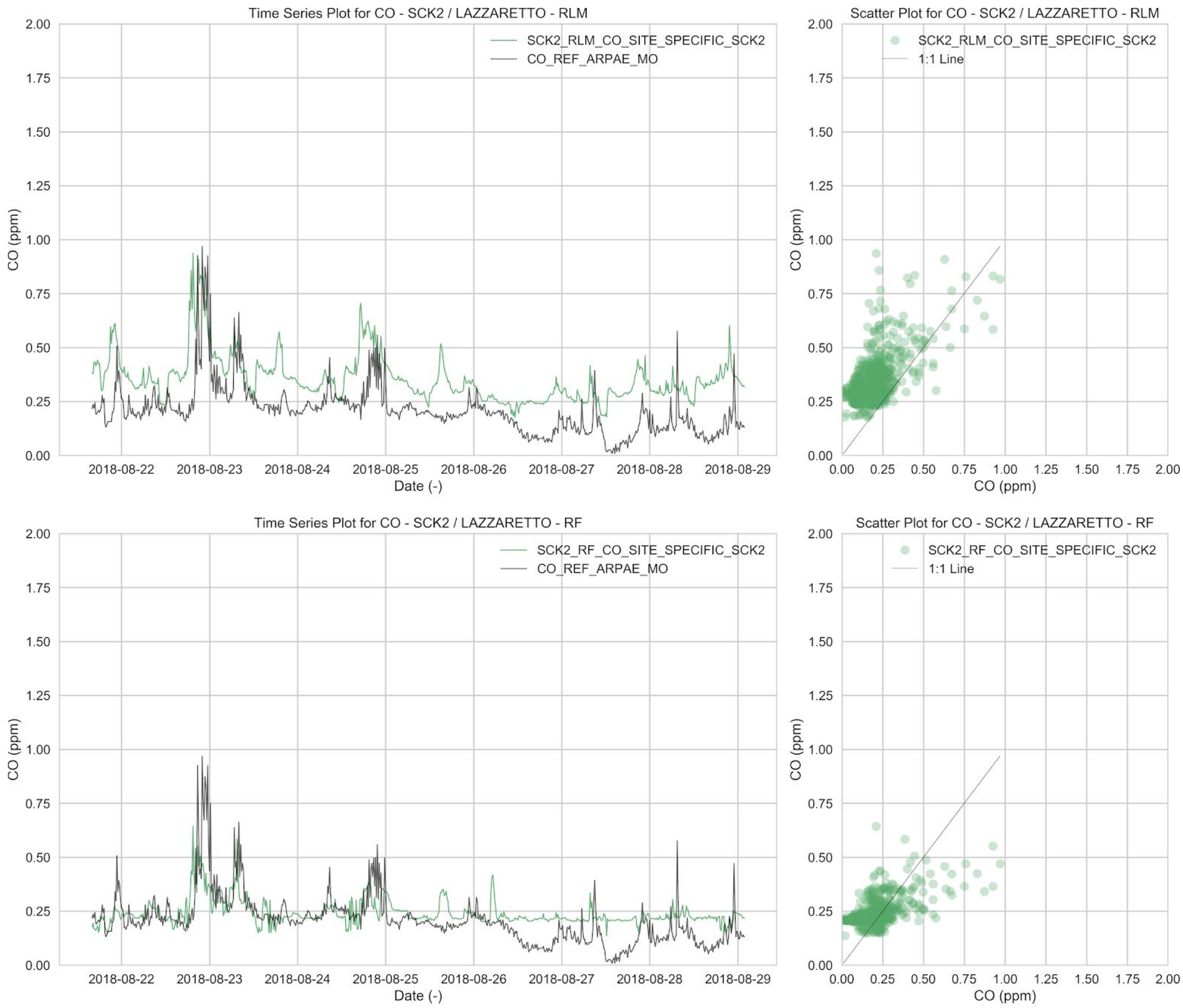


Figure 38. Extrapolation of CO model to other devices.

Finally, as a summary, all the models summarized in Table 14 are shown in Figure 39, in the shape of two target diagrams (separate for CO and NO_2). Each of the colours show a different model (OLS, RLM, random forest and XGBoost), and each entry of each colour is a different device. Some of the models can perform better, being the machine learning (RF) the best of them, however the performance decays when applied to other devices. This is the case for both pollutants, while NO_2 shows a lower performance on average due to the lower sensitivity at low actual pollutant concentrations.

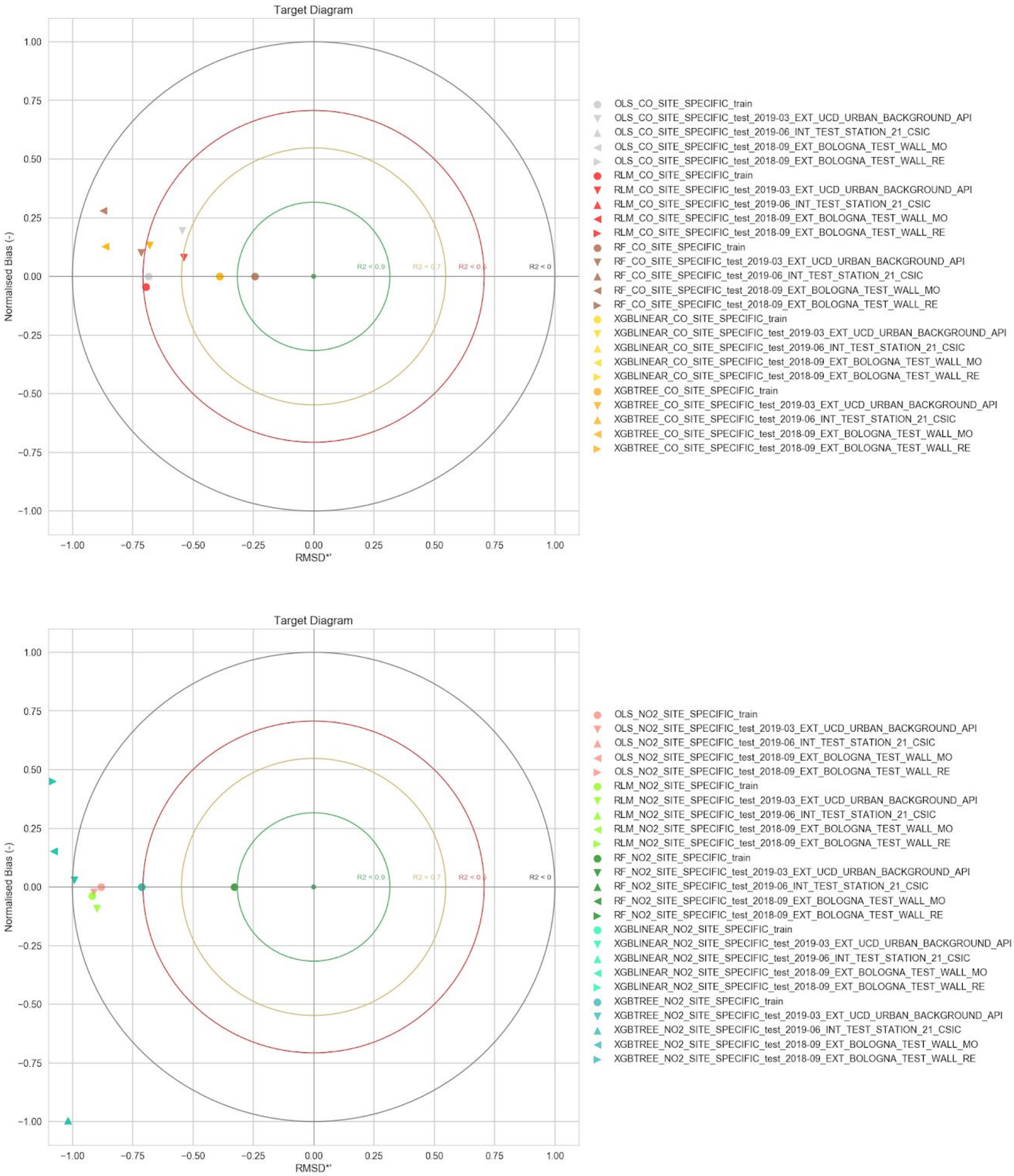


Figure 39. Target Diagram for CO and NO2 models

In order to determine how much time the sensors should be deployed with reference data, several model iterations are run with varying splits for the training data. Aiming to get a minimum target for R^2 of that of the baseline model during the test set, which always left 1 month of data. This is shown in Figure 40, for both pollutants, and results in a minimum deployment of one month in the case of the CO and NO2. It should be noted that this has been only tested for one device, and it is meant as a demonstrator of this technique in case there will be more data available.

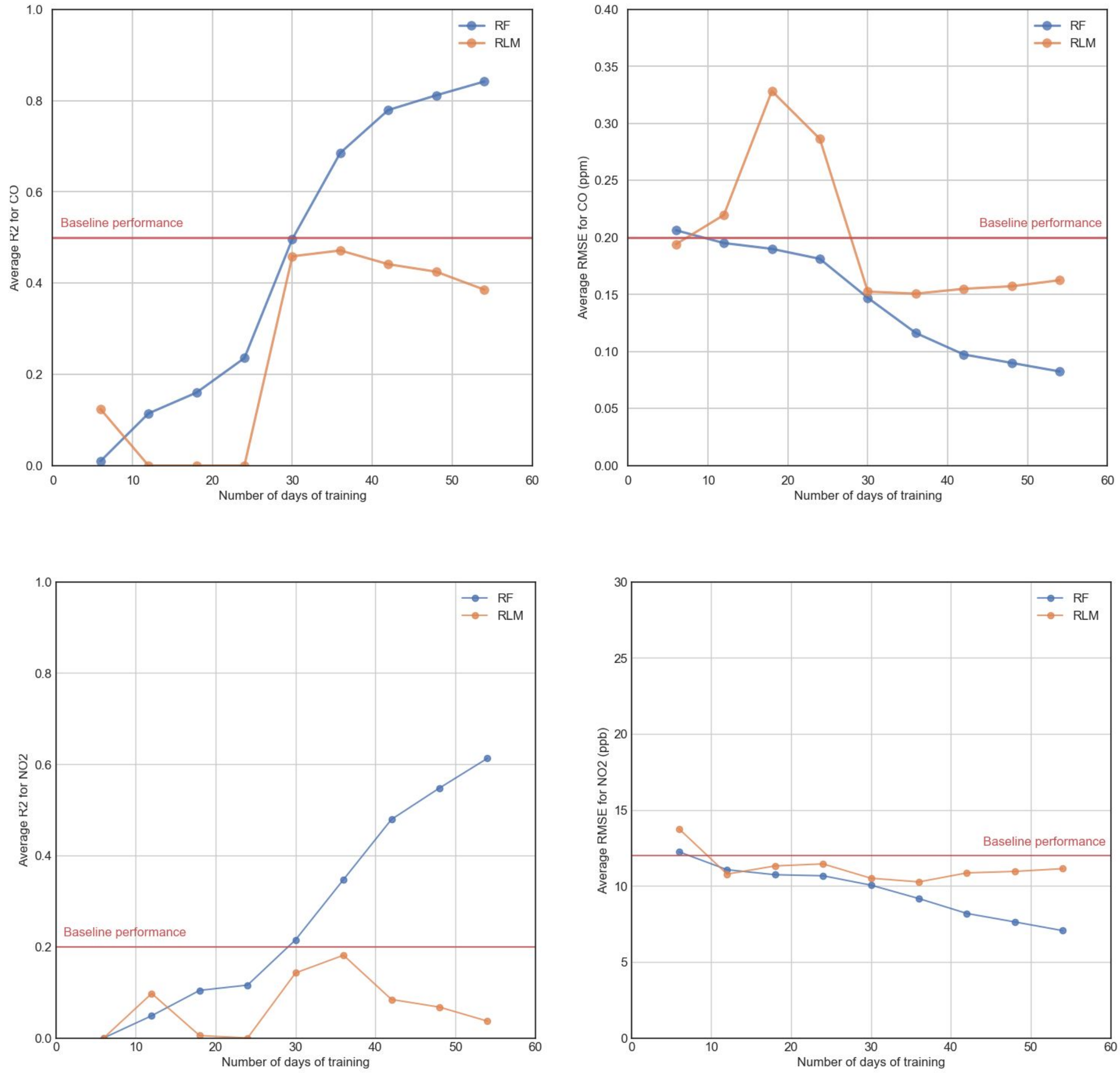


Figure 40. Minimum co-location conditions for baseline model improvement

6.4.2.2 Generic models

In the next paragraphs, the results for the generic model approach will be discussed. The training for each of the models is conducted with at least one device from each site, while the testing is performed on the rest of the devices. Table 15 shows the metrics summary for each of the models and devices.

City/ Location	Device	Pollutant	Baseline Model	Linear Model (RLM)	Random Forest	XGBoost
			R^2 / RMSD (ppm CO, ppb NO_2)			
Bologna/ Lazzaretto	SCK2	CO	0.4 / 0.2	0.4 / 0.2	0.8 / 0.1	0.3 / 0.1
		NO_2	na	na / na	0.7 / 5	na / na
	SCK3	CO	0.3 / 0.2	0.4 / 0.5	0.6 / 0.1	0.2 / 0.1
		NO_2	na	na / na	0.2 / 7	na / na
Dublin/ DCC	5262	CO	0.5 / 0.2	0.4 / 0.15	0.8 / 0.1	0.8 / 0.1
		NO_2	0.15 / 12	0.1 / 11	0.9 / 4	0.4 / 9
	5565	CO	0.6 / 0.1	0.7 / 0.1	0.7 / 0.1	0.7 / 0.1
		NO_2	0.15 / 11	0.2 / 10	0.6 / 8	0.3 / 9
Barcelona/ Palau Reial	9941	CO	na / 0.1	na / na	na / na	na / na
		NO_2	na / na	na / na	0.7 / 9	0.3 / 14

Table 15. Metrics summary for generic model approach

Figure 41 shows the target diagram for the models tested in the generic model approach, for each of the pollutants. As seen in Table 15, the machine learning model starts to outperform the rest of the models, showing higher correlation values and lower RMSDs. The amount of data collected is not sufficient to extract general conclusions about the procedure, but this sets guidelines for further testing and data collection, as discussed in the Future opportunities section. In Figure 41, the target diagram shows that the devices tested with the machine learning model are consistent in results and that the model is able to extrapolate to other devices, such as the LLS in DCC (device 5565), with R^2 = 0.6.

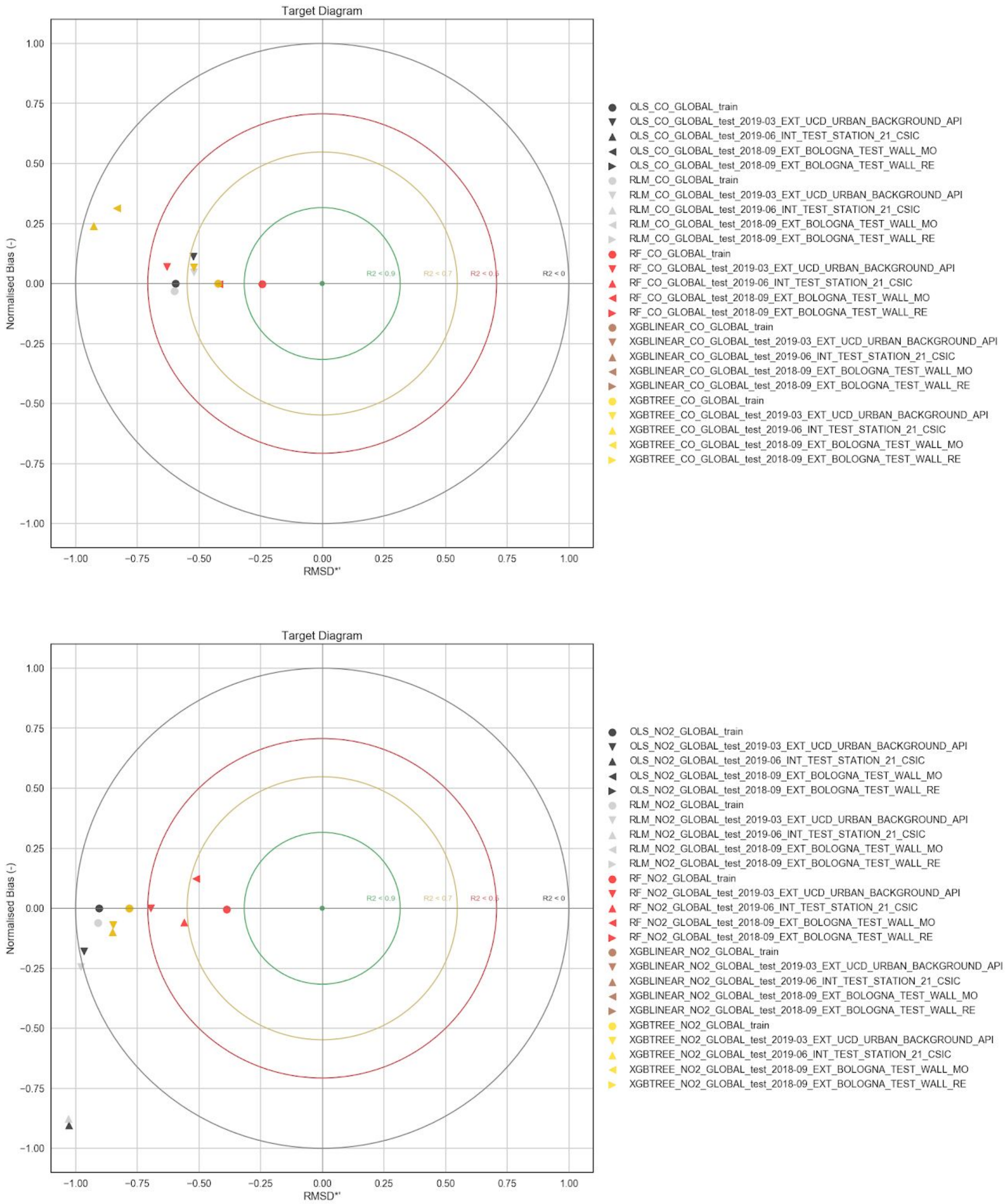


Figure 41. Target Diagram for CO and NO2, using generic model approach

In Figure 42, a comparison between the reference and the pollutants calculated with this approach is shown, for example devices that were not used for the model calculation.

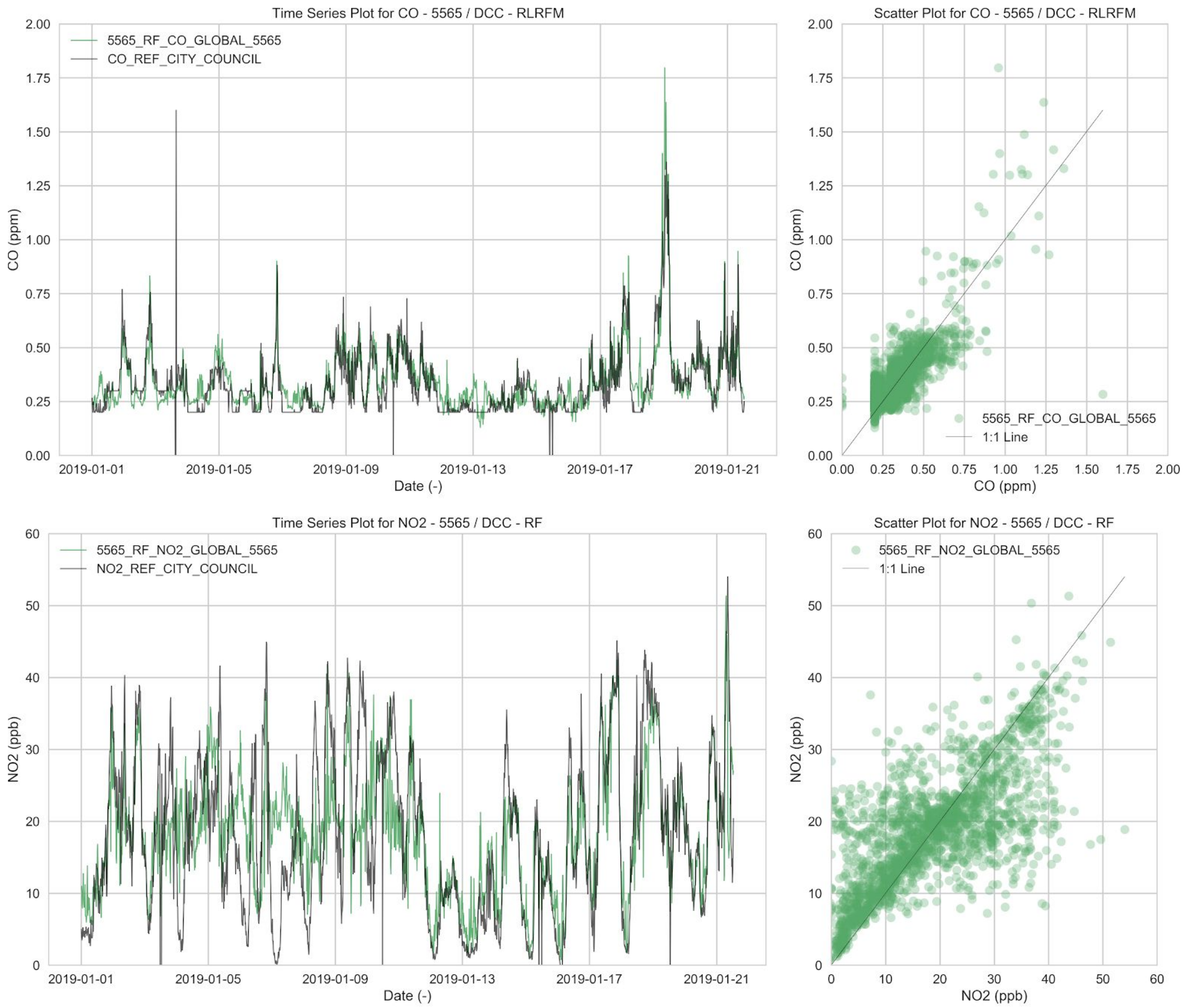


Figure 42. Model comparison for CO and NO2 at DCC with device 5565, generic model approach

6.4.3 Additional comments

Given the limited amount of data collected during the iSCAPE project, a study has been conducted trying to assess different available possibilities, using a data driven approach. The results shown in this section aim to set guidelines for data modeling approaches, but aren't in any case definitive. As mentioned in Kizel et al. (2017) [17] and Dušan et al. (2018) [18], the models generated for the pollutant estimation will be as reliable as the multi-sensor platform that collects them, and their careful analysis will result in proper regression coefficients. For this reason, a larger amount of valid data will be necessary to be able to bring these models into production, which is being planned with different institutions (see Future opportunities).

7. Commercial opportunities

In this chapter, the final commercially available products for the SCK 2.1 are detailed. Furthermore, the results from the different deployments carried out with the LLSs are discussed, as well as other parallel studies that were carried out within the scope of the iSCAPE project.

7.1 The SEEED Studio Kit

Last January 2019, we partnered with SEEED Studio, the biggest open hardware and retailer in China to sell our commercial version of the Citizen Kit.

Two available packs are available at the store: the Smart Citizen Kit (Figure 43) and the Smart Citizen Starter Pack (Figure 44). The former includes an SCK2.1 with a PMS5003 sensor, whilst the latter includes a LiPo battery, a USB charger and a micro sd-card.

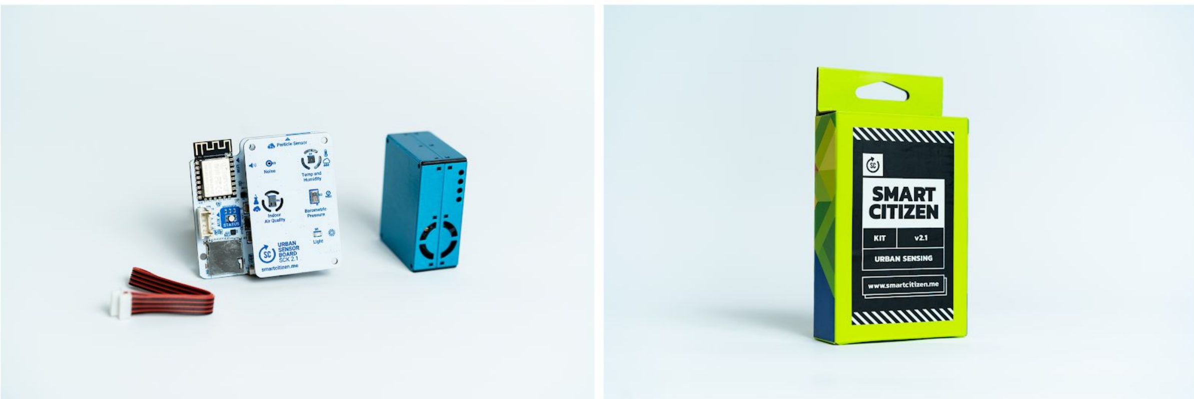


Figure 43. Smart Citizen Kit. Available at SEEED Studio

At t the moment we are under negotiations with the SEEED Studio store in order to manufacture the enclosures, PM Sensor board and the Gases Pro Board. All devices/ parts will be available to buy through their online store.

Figure 44. Smart Citizen - Starter Pack. available at SEEED Studio

7.2 Future opportunities

As mentioned above, the SCK 2.1 is commercially available through SEEED Studio, although it is not the only channel. Consultancy services are also available for larger batches, generally aimed at research projects. A summary of the SCK V2.1 sales is detailed in Table 16, and shown visually in Figure 45.

B2B Sells	
Bristol University for KWMC	200
IS Global for Climatic Shelters	102
Barcelona Council for DECODE	25
UAB with IS Global for Attention	25
Wuppertal Inst. with UN Habitat for Urban Pathways	10
Fraunhofer Institute for Industrial Engineering IAO	8
Total	**370**
B2C Sells	
Direct Sells on SEEED Store	401
Total sells	771

Table 16. Sales summary for SCK V2.1 through SEEED Studio and consultancy services from May to October 2019

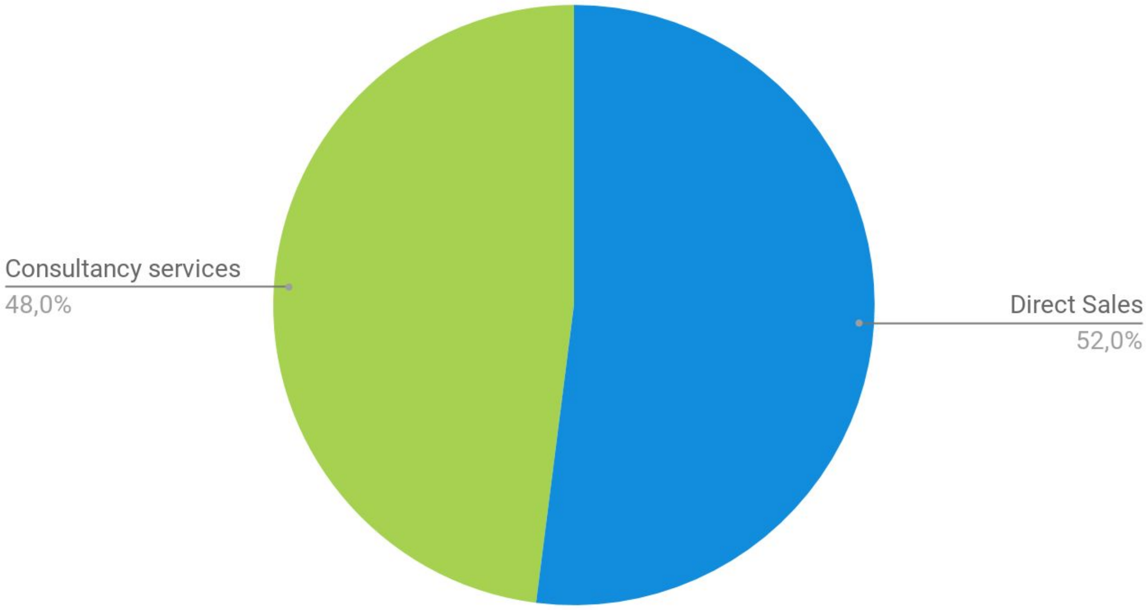


Figure 45. Sales summary for SCK V2.1 through SEEED Studio and consultancy services

7.2.1 Partnerships

During the last months of the project, the Smart Citizen team partnered with multiple research centres, which are part of the iSCAPE project consortium and who are have contributed to the laboratory and field validation of the Smart Citizen technology. In addition, the sale of commercial services and technology to research institutions such as the Wuppertal Institute in Berlin[42] or ISGlobal[43] in Barcelona have begun. These institutions have purchased more than 100 sensors for different research projects, to date. The iSCAPE technology has already been used in other H2020 projects such us the DECODE[44] project, where privacy-by-design technologies were applied to participatory sensing.

Also, Smart Citizen is aiming at maintaining an ongoing relationship with all the Living Labs that are part of the consortium. Through ENOLL, the team is promoting similar research approach to the network of more than 400 labs that are potential customers of our products. KWMC, a Living Lab in Bristol, has already purchased more than 200 sensors.

Furthermore, partnerships with local educational institutions in Barcelona have brought sensors to schools and public libraries thanks to a collaboration with

[42] Wuppertal Institute: https://wupperinst.org/
[43] ISGlobal website: https://www.isglobal.org/ca/
[44] Decode Project: https://www.decodeproject.eu

multiple stakeholders including Universitat Autonoma Barcelona (UAB), ISGlobal and the Barcelona City Council. The partnership has already led to three projects and the results are put into practice / action, projects include: Projecte Atenció[45], Climate shelters in schools[46] and BiblioLab Ciencia Saludable[47].

7.2.2 Hardware

Concerning the hardware development roadmap for the sensors in the SCK 2.1 and Living Lab Stations, and given the design for modular architecture in the hardware, future sensor improvements and implementations are planned, especially for the PM sensor.

In the case of electrochemical sensors, as mentioned in chapter 5, having proved the validity of the solution presented with the Gases Pro Board, the introduction of a single electrochemical sensor board, resembling the ISB of Alphasense, is also under consideration, which could be directly branched to the SCK through its auxiliary port.

In order to complete the solution for air quality measurements, other NDIR (non-dispersive infrared) CO2 sensors are under study, as well as more specific VOC (volatile organic compounds) sensors, able to measure indoor quality for pollutants such as formaldehyde.

Additional testing for the LLS is under discussion with different potential collaborators, such as the FMI (Finnish Meteorological Institute), Alphasense Ltd, UCD (University College Dublin), and the Barcelona local authorities. These tests would aim to complete the results extracted from the sensor evaluation campaign detailed above, further improve the models until production state as well as generating guidelines for sensor deployment, such as the ones presented in the previous section 6, regarding deployment conditions and co-location durations.

45 http://projecteatencio.cat/
46 https://www.barcelona.cat/barcelona-pel-clima/en/climate-shelters-schools
47 https://www.isglobal.org/-/bibliolab-ciencia-ciutat-saludable

8. Outreach activities and synergies

The following chapter briefly summarizes a selection of the exploitation activities carried out to maximize the impact of the project results on air quality measurement solutions.

8.1 Promotional events and other dissemination activities

As part of the project exploitation strategy, we have participated in several events with a specific emphasis on covering a large number of targets to increase the impact of the project and foster the commercial exploitation of the results.

- **Smart City Expo World Congress** (Barcelona, ES, 2016) Presentation at the DSI4BCN, Barcelona City Council
- **Oxford University, The Institute for Science, Innovation and Society** (InSIS). (Oxford, UK, 2017) Seminar on CS and Innovation Policies
- **IED Istituto Europeo di Design** (Barcelona, ES, 2017) Presentation at the DSI4BCN, Barcelona City Council
- **Smart City Expo World Congress** (Barcelona, ES, 2017) Seminar on Design for CS and Data Visualization
- **Mobile World Week (MWC)** (Barcelona, ES, 2018) Round table on Smart Cities and Data Analytics with Francesca Bria, Barcelona CTO, Esteve Almirall, ESADE, et al.
- **Ciutat Oberta** (Barcelona, ES, 2018) Round table on CS and Data Ownership with Olaguer Segarra et al.
- **Consensus Conference** (New York, US, 2018) Exhibition on the 4th annual blockchain technology summit on the Streamr booth on real-time distributed air quality technologies
- **Green week partner event** CS and Air quality (Brussels, BE, 2018) Green Week partner event with Ground Truth 2.0, Curieuze Neuzen and hackAIR
- **1st ISCAPE Summer School** (Hasselt, BE, 2018) One day workshop at Hasselt University to promote the project sensor technologies within the regional community

- **Hackair and JRC Round Table** (Frankfurt, BE, 2018) Round table on new opportunities for air quality sensing to present the project results
- **Resilient Cities Conference** (Frankfurt, GE, 2019) Exhibition both to promote the project technologies on the Global Forum on Urban Resilience and Adaptation bringing together public decision makers from all over the world
- **Science is Wonderful!** (Brussels, BE, 2019) Exhibition to promote and disseminate H2020 scientific project results to the general public
- **2nd ISCAPE Summer School** (Hasselt, BE, 2019) One day workshop at Hasselt University to promote the project sensor technologies within the regional community
- **MISION Neutral Carbon and Smart Cities** session (Madrid, ES, 2019) Coordination meeting for future exploitation of the project results for the upcoming H2020 Mission Challenges

8.2 Promoting technological integration with other EU funded platforms

Along with the project, we have succeeded to establish synergies with multiple EU funded platforms to help promote, share and enhance the iSCAPE results:

- **hackAIR[48];** Collective awareness platform for outdoor air pollution is an H2020 project (GA 688363) that develops and pilots an open platform to enable communities of citizens to easily set up air quality monitoring networks. hackAIR in collaboration with JRC invited IAAC on a round table on new opportunities for air quality sensing: Lower cost sensors for public authorities and CS initiatives. The results of the session are collected on: "Joint Statement on new opportunities for air quality sensing - lower-cost sensors for public authorities and CS initiative" Schade S et al. (2019) [24].
- **Decode Project;[49]** Decentralised Citizens Owned Data Ecosystem is an H2020 project (GA 732546) focusing on giving people ownership of their data. The project provides tools that put individuals in control of whether they keep their personal data private or share it for the public good. IAAC worked close to the consortium to implement a pilot on citizen CS data governance. The ISCAPE Citizen Kit was integrated with the DECODE software platform

48 https://www.hackair.eu/
49 https://www.decodeproject.eu/

as part of a pilot in Barcelona with 25 citizens. The objective was to demonstrate the technical challenges of collating and storing a stream of citizen-sensed data, while also enabling those citizens to control what information is shared with whom, and under which conditions.

- **MUV Project[50];** Mobility Urban Values is an H2020 project (GA 723521) focusing on behaviour change in local communities in an entirely novel approach to reducing urban traffic. IAAC has given consultancy support to the project consortium on low cost air quality sensor development and calibration by exploiting the ISCAPE results.
- **Grow Observatory[51]** is an H2020 project (GA 690199) that creates a sustainable citizen platform and community to generate, share and utilise information on land and soil data. IAAC as part of the consortium has enhanced the ISCAPE Citizen Kit to collect soil moisture data and has worked on integrating the hardware with the Grow Observatory platform.

[50] MUV2020 Project: https://www.muv2020.eu/
[51] Grow Observatory Project: https://growobservatory.org/

9. Conclusions

This deliverable demonstrates the advancements achieved during the technical development of low-cost sensors in terms of hardware and software solutions. This effort focused mainly on providing a reliable solution for air quality sensing in the field of CS, as well as an advanced framework for more advanced air pollution research using low-cost sensor technology. Both objectives were fulfilled with an open, modular and flexible approach, developing a set of hardware components that could be used by citizens and researchers alike, aiming to optimize the research and development effort by using reusable software and existing platforms.

The development followed an agile methodology and incremental approach, with design iterations that considered the feedback provided by the end-users, both citizens and researchers. A continuous feedback channel allowed the improvement of the proposed solutions, finally resulting in the commercial exploitation of the Citizen Kit, and the successful deployment of the Living Lab Stations as part of intervention monitoring campaigns. In retrospective, this feedback was considered critical, and it allowed for faster development, resulting in a more reliable end solution.

Low-cost sensors are often regarded as not being sufficiently reliable in terms of data accuracy. For this reason, a special effort was conducted to ensure the validity of the measured data, with the evaluation of the sensors in the field in measurement campaigns. Limitations and potential improvements were identified and, when possible within the scope of the project, implemented. An important advantage of the project mindset, was that the solutions were designed with a modular approach in mind, and future opportunities can build on top of the solutions hereby presented. After analysis of the deployment data, guidelines for deployment and data collection are given, such as installation conditions, duration of the data collection, and modeling approach.

The final CS solution is a commercially available sensor kit (Smart Citizen Kit and Smart Citizen Starter Pack, at SEEED Studio Store) at a price below 100€. This solution is complemented with a comprehensive setup procedure, extensive documentation and an online platform in which users can interact with their data in near real-time. These features were considered critical for the engagement of the users and communities, alongside with ease of use and data reliability. In the case of the Living Lab Station, further evaluation prior commercialisation is planned, beyond the iSCAPE project, aiming to expand the results shown in this deliverable.

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