



Project Details

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The LEARN Consortium

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Project Aim

LEARNIng about the status of air quality in schools and its impact on the cognition of children is a major cornerstone in LEARN. For that, we want to overcome the barriers of the currently existing technologies and take a bold step towards developing and deploying novel sensors to

detect the presence of possibly harmful air pollutants such as volatile organic compounds and ultrafine particles.

We will measure and characterize indoor and outdoor air pollutants and evaluate the presence of biomarkers of exposure and their effect on children's cognition while trying to recapitulate those effects using *C.elegans* as a biosensor. Moreover, we will use advanced human-based in vitro models of lung and skin coupled with a revolutionary multi-sensing device to investigate their mechanisms of toxicity in real time.

Novel remediation strategies will be explored to improve air quality and promote children's quality of life and life expectancy. The scientific achievements expected to result from LEARN will unlock a large technology potential in IAQ for decades to come, leading to disruptive societal and economic impacts steaming from a radical improvement in the quality of life of children in Europe. Project LEARN is part of the European indoor air quality and health cluster IDEAL.

Document Details

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The following table describes the main changes done in the document since it was created.

Revision	Date	Description	Author (Organization)
V1.0	March 2026	Initial draft	TU/e
V1.0	March 2026	[INL contribution]	INL
Final	March 31, 2026	Final version	INL & TU/e

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Abstract

The present document is Deliverable D4.5 of WP4 “Novel Sensors UFPs and VOCs.” It reports on the progress toward deploying sensor prototypes in the field.

For the VOC sensor developed by INL, the deliverable presents the description of the deployment of VOC sensor prototype at a school.

For the UFP sensor developed by TU/e, the deliverable describes the three-stage approach to ultrafine particle sensing—capture of UFPs in a liquid droplet, transport of the droplet via electrowetting-on-dielectric (EWOD), and detection of UFPs using a fiber-tip optical sensor—all to be integrated on a single printed circuit board (PCB). Due to the later integration of TU/e into the consortium, the adoption of a fundamentally new sensing concept, and practical challenges in the particle capture stage, the UFP sensor prototype has not yet reached full field-deployment readiness. We can therefore not report on the testing of a UFP sensor prototype in the field. Nevertheless, a first proof of principle of the complete detection chain has been achieved: inertial capture of UFPs into a droplet, transfer to the detection system, and quantitative single-particle detection. This deliverable therefore reports on the current status of each stage, the progress toward integration on a single PCB, and the path toward field validation.

1 Introduction and Context

Deliverable D4.5 “Sensor Prototype (in the field)” is a demonstrator deliverable within Work Package 4 (WP4: Novel Sensors UFPs & VOCs). Its objective is to report on a field-deployable sensor prototype for the detection of both ultrafine particles (UFPs) and volatile organic compounds (VOCs).

In the sequence of the validation of the VOC prototype in laboratory environment done in D4.4, our aim is to report the work subjacent to the deployment of the VOC prototype on a school environment. The deployment of the VOC prototype, hindered by a laser component a malfunctioning on February 2025, is sequentially to the work reported in two manuscripts: 1) Optics Express, <https://doi.org/10.1364/OE.564577> and 2) Environmental Technology and Innovation, (<https://doi.org/10.1016/j.eti.2026.104895>).

As reported in previous deliverables D4.1–D4.4, the development trajectory for the UFP sensor evolved substantially after TU/e joined the LEARN consortium as a new partner, replacing the originally planned partner. The TU/e team introduced a fundamentally new sensing concept based on fiber-tip optical sensors capable of detecting individual ultrafine particles. While this approach provides a significantly higher long-term innovation potential, it requires more fundamental research and laboratory validation steps before reaching a field-deployable prototype.

The change of partner caused an unavoidable delay: TU/e officially joined the consortium retroactively one year after the project start, with two PhD students commencing their research only in Nov. 2023 and Apr. 2024, respectively. Consequently, the UFP sensor development timeline shifted by approximately 18–24 months relative to the initial plan. This was flagged at an early stage and the consortium agreed that the anticipated extension of the project by six months would be needed to achieve the goals.

Despite the late start, the TU/e team quickly reported the detection of particles with diameters <100 nm in a solution, using simple fiber equipment that is easily deployed in the field. The development of a complete field prototype encountered several practical challenges during integration, particularly in Stage 1 (particle capture). These included delays in implementing high-voltage electrostatic delivery due to the need to comply with laboratory safety regulations, and lower-than-expected capture efficiency using inertial forces alone, requiring prolonged exposure of the droplet to the air flow to reach detectable particle concentrations. Consequently, at the time of writing, the UFP sensor has reached the level of a proof-of-principle laboratory demonstrator rather than a deployable field prototype. A complete chain - inertial capture of UFPs, manual transfer of the particle-laden droplet to the detection system, and detection using the fiber-tip optical sensor - has been successfully demonstrated, and quantitative particle concentration measurements can be derived from the recorded detection events. The details of these achievements and remaining challenges are described in Section 3.

This deliverable is structured as follows: Section 2 is reserved for the INL VOC sensor contribution. Section 4 provides the conclusions for this deliverable. Section 3 presents the TU/e UFP sensor, describing the three-stage approach, the current status of each stage, and the progress toward integration of all three stages in single device.

2 INL Volatile Organic Compound (VOC) Sensor

Introduction

In the sequence of the validation of the prototype in laboratory environment done in D4.4, our aim is to report the work subjacent to the deployment of the VOC prototype on a school environment.

As reported in the deliverables D4.1-D4.4, the VOC sensor is composed of 5 modules: laser, the ionization chamber integrating the transimpedance amplifier and SiO₂ suspended nanomembranes, and the PC. The laser component presented a malfunctioning on February 2025. After several attempts to troubleshoot remotely, only in June 2025 we had a service repair from the supplier. This hindered our planned work.

To mitigate the problem, the INL WP4 team contacted a local school in Braga to perform the field validation. At the same time, we evaluated the best available engineering options to transform the prototype at laboratory stage development into a transportable prototype taking in account also laser safety considerations.

A new timeline was sent to the PO for the workplan from September 2025 to April 2026 is shown in Table 1.

Table 1 Restructured workplan to complete D4.5 (November 2025)

Year	Month	Tasks to complete D4.5
2025	June-September	Evaluation on how to integrate the components in the optical table with the PCs modules. Ordering and reception of a cabinet for PC component and a transportable optical table.
	October	Evaluation and ordering of the components to minimize the laser safety risks at a school environment
	November	Assembly of a transportation box
	December	Validation tests in the laboratory with the transportable version of the prototype
2026	January	Validation of the prototype at a local school
	February	Continuation of the validation of the prototype at a local school
	March	Report – conclusion of D4.5

Based on what was presented in Table 1, the team delineated the critical risks and the correspondent mitigation plan as shown in Table 2.

Table 2 Critical Risks and Mitigation Plan as presented in the pre-emptive justification (November 2025)

Month	Tasks to complete D4.5	Critical Risks	Mitigation	Status
June-September 2025 M39-M42	Design of component integration for field test with optical table and PC modules. Ordering, delivery and construction of a electronics and PC cabinet and a transportable optical table.			Achieved
October 2025 M42	Evaluation and ordering of the components to minimize the laser safety risks at a school environment	Lead time delays	Order with sufficient time in advance	Achieved
November 2025 M43	Assembly of a transportation box	Need to order extra optomechanical components	Engage INL mechanical workshop to speed up build, leaving time for reordering missing components	Ongoing Interim Checkpoint at end M43
December 2025 M44	Validation tests in the laboratory with the transportable version of the prototype	Test failure	Leave equipment inside lab to replicate lab experiments for failure investigation	Pending Interim Checkpoint at end M44
January 2026 M45	Validation of the prototype at a local school in Braga, Portugal	Transportation damage	An insurance will be done covering transportation damage.	Pending Interim Checkpoint at end M45
February 2026 M46	Continuation of the validation of the prototype at a local school	Software failure	Use back-up system available at INL premises for software debugging and validation	Pending
March 2026 M47	Report – conclusion of D4.5			Pending

A new date for the milestone was presented.

Table 3 Milestone new date as in the pre-emptive justification

Milestone No	Milestone Name	Due Date	New date
8	UFP/VOCs Sensor Prototype in the field (TRL 3/4)	M44	M47

Along those mentioned, in the pre-emptive justification we also delineated a fallback plan and a secondary risk mitigation plan as shown in Table 4.

Table 4 Fallback Plan and Secondary Risk Mitigation

Month	Tasks to complete D4.5	Critical Risks	Mitigation	Secondary Risks	Fallback plan
June-September 2025 M39-M42	Design of component integration for field test with optical table and PC modules. Ordering, delivery and construction of a electronics and PC cabinet and a transportable optical table.				
October 2025 M42	Evaluation and ordering of the components to minimize the laser safety risks at a school environment	Lead time delays	Order with sufficient time in advance		
November 2025 M43	Assembly of a transportation box	Need to order extra optomechanical components	Engage INL mechanical workshop to speed up build, leaving time for reordering missing components	Difficulties in assembling the components already at INL	Seek expertise and hand-on-advise from a colleague that has built similar optical boxes and is working partial-time on other projects in the group
December 2025 M44	Validation tests in the laboratory with the transportable version of the prototype	Test failure	Leave equipment inside lab to replicate lab experiments for failure investigation		
January 2026 M45	Validation of the prototype at a local school in Braga, Portugal	Transportation damage	An insurance will be done covering transportation damage.	Irreparable damage of components during transportation	INL WP4 team has replacements for all components of the prototype. If damage related to laser components the team will seek immediate assistance from laser manufacturer
February 2026 M46	Continuation of the validation of the prototype at a local school	Software failure	Use back-up system available at INL premises for software debugging and validation	Hardware damage of components	INL WP4 team has replacements for all components of the prototype
March 2026 M47	Report – conclusion of D4.5				

Engineering enhancements – from the laboratory to the field

As of June 2025, the prototype has been tested in a laboratory environment for single compounds and for gas matrices.

In a first step, we have successfully integrated a pulsed (60 kHz, 230 fs), wavelength tuneable (340 nm to 440 nm) laser with suspended SiO₂ nanomembranes of 600 nm thickness for efficient THG in the VUV. We demonstrated that this tuneable quasi monochromatic VUV is capable of photoionizing molecules in the gas phase derived from SVP concentrations of ethanolamine and eucalyptol. Furthermore, through the photoionization of eucalyptol at 360 nm THG pump laser illumination we indirectly demonstrate the generation of VUV down to 120 nm, significantly lower than what has been demonstrated to date and with an associated energy of 10.3 eV above the 8.8 eV bandgap of SiO₂. The photoionization current was determined to be linearly dependent on the gas concentration for ethanolamine. Furthermore, our investigation places an upper and lower bound on the ionization potential of eucalyptol of 10.3 eV and 9.5 eV, respectively. The work developed was reported in Optics Express (<https://doi.org/10.1364/OE.564577>)

Further work was developed for the selective detection in real-time of VOCs in a gas matrix. We demonstrated for the first time the molecular specific and real-time detection of a calibrated mixture of benzene, toluene, ethylbenzene and xylene isomers (BTEX) VOCs using SIPS. Unlike conventional PID sensors, reporting TVOC, and portable GC-MS (not in real-time), SIPS approach offers real-time and molecular selective detection. We showed that SIPS can selectively detect BTEX compounds at threshold limit value–time-weighted average (TLV-TWA) concentration levels in real time, without the use of bottled carrier gases and with immunity to confounding background signals from other VOCs. The work has been reported in the manuscript published in Environmental and Technology Innovation (<https://doi.org/10.1016/j.eti.2026.104895>).

Since SIPS operates entirely under atmospheric pressure conditions, field testing was estimated to be feasible. However, refinements and adjustments had to be made so the prototype could be tested in a school environment, such as:

- Assembly of a transportation box with all the optomechanical components custom designed
- Installation of a temperature sensor for monitoring environmental conditions inside the encasing
- Installation of a pump for air collection and integration with the detector module
- Implementation of components to minimize the laser safety risk at school environment
- Software integration between the commercial laser module software and LabVIEW code written by the INL WP4 team.

Assembly of a transportation box

The INL WP4 team built an encasing by customising optomechanical components to the dimensions of the optical table where the main components like the laser, detection chamber and transimpedance amplifier were fixed. The encasing was done stepwise and recurring to a metallurgical company that was responsible for cutting the metallic commercial pieces with millimetric accuracy. Also, due to the lack of commercial pieces with the right dimensions, one top plate was designed, fabricated and anodized for this encasing.

Subsequently, the encasing was fit adjusted to a transportable unit. The hardware components were connected to the software components in a vertical cabinet.



Figure 1 The SIPS prototype enclosed in the transportation box, the transportable table and vertical cabinet

The hardware components were connected to the software ones located in a vertical cabinet as shown in the figure below.

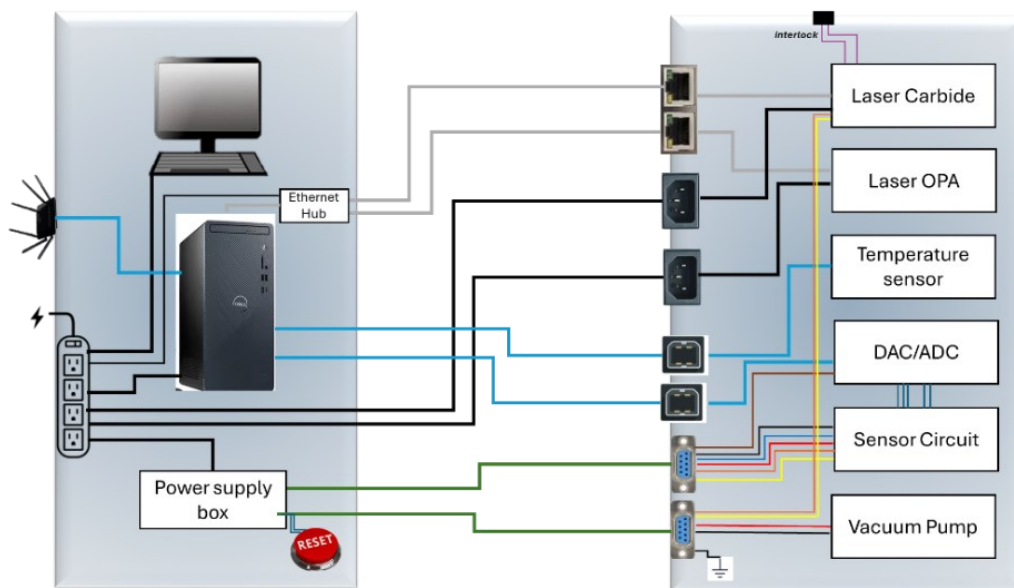


Figure 2 Schematic of electrical connections between the components located in the vertical cabinet (left) and the components in the transportable table (right).

Temperature monitoring

The laser efficiency depends on temperature. Since the VOC prototype was encased in a box it was installed a temperature sensor with the required circuit, the Arduino board to read the digital output and an USB cable to transfer the information as shown in the figure below.

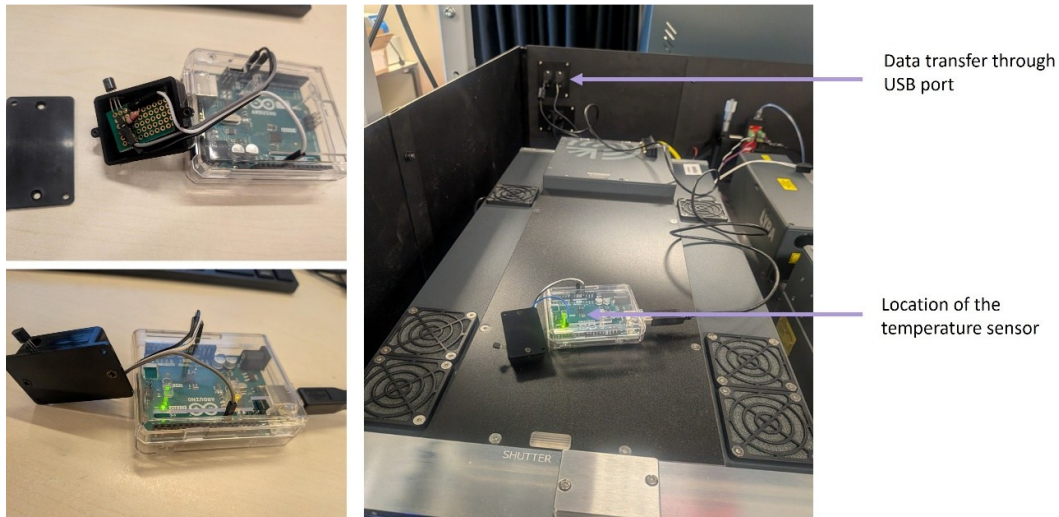


Figure 3 The temperature sensor was installed on the top of the CARBIDE where this parameter matters the most for the correct functioning of the laser.

Air collection

For the air collection was installed a micro pump vacuum as shown in the figure below. The pump was calibrated for collecting air at a flow of 200 mL/min.

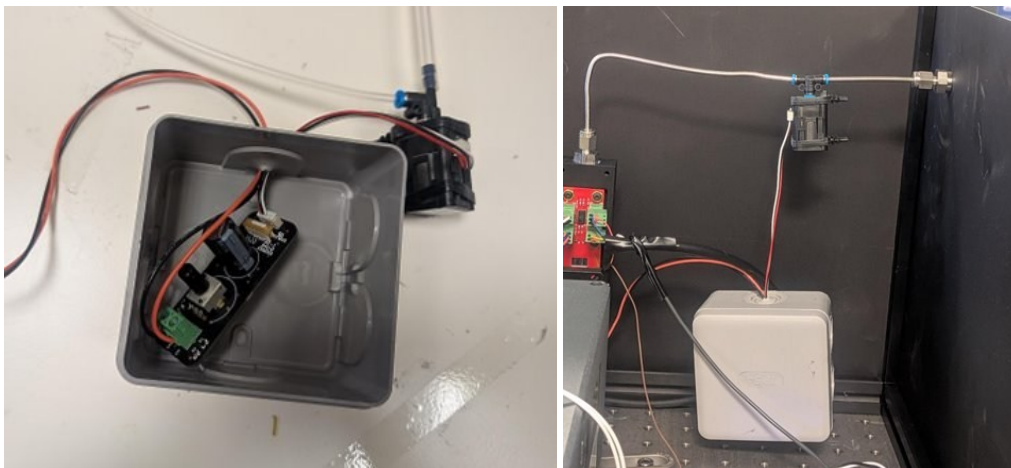


Figure 4: Photographs of the micro pump calibrated to collect air at a flow rate of 200 mL/min.

Safety features

A safety interlock laser was installed as an additional preventive mechanism as shown in the figure below. With this implementation, was sought that as soon as the lid of the laser box would get opened this would trigger a signal to laser module to be shut off. To resume the laser module operation a two-step routine had to be verified: 1) the lid must be closed 2) the reset button pressed has mandatory to be pressed. Additionally, were implemented physical barriers to keep the encasing closed.

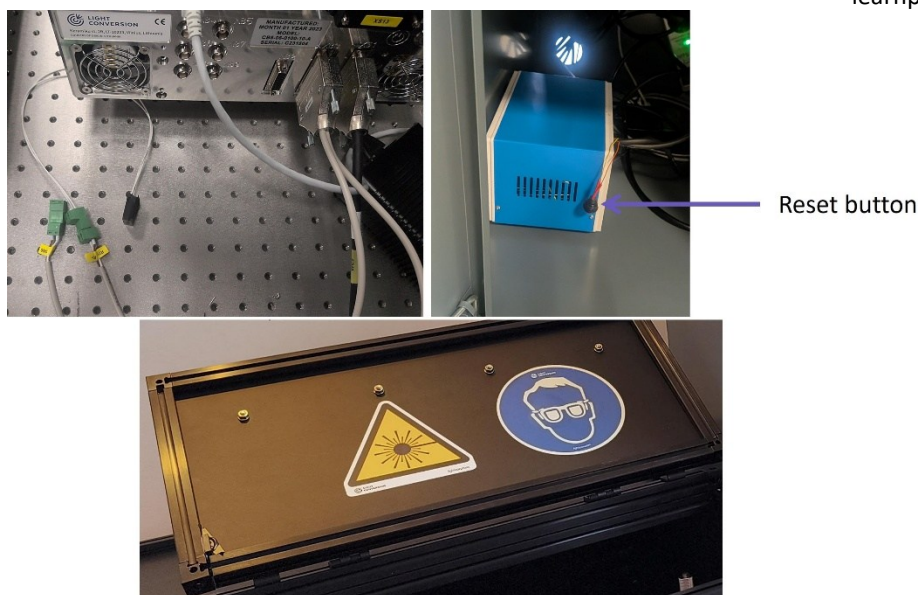


Figure 5: Photographs of interlock connected to lid and safety signs placed on lid facing inside.

Software integration

To automate the signal acquisition routine the commercial laser module software was integrated with the LabVIEW code written by the INL WP4 team. A scheme of the routine implemented between both is depicted in the figure below.

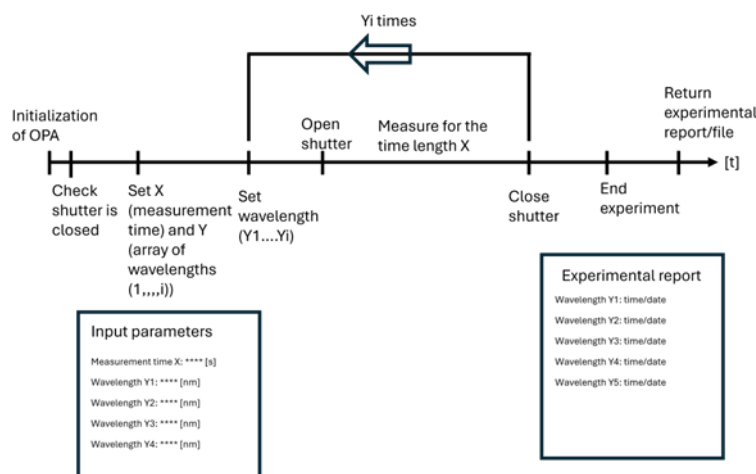


Figure 6: Scheme for the software integration for automation of the signal acquisition.

Validation before transportation

Before deployment of the prototype at the school, we made a simple validation test in the laboratory with the transportable version of the prototype. To this end we placed a bottle of isopropanol near the outlet. The results obtained show a difference in voltage attributed to the photoionizing molecules in the gas phase derived from isopropanol.

Deployment of the VOC prototype

This section describes the deployment of the SIPS prototype from the INL laboratory to the school located in Braga, Portugal, in particular:

- transportation from INL laboratory to school
- VOC prototype routine validation
- Comparative validation of the VOC prototype

Transportation of the VOC prototype

Despite the closeness of INL laboratory to the school, the transportation had to be done in two days. In the first day the operation had to be adjourned due to severe weather conditions that affected Portugal in January. In the first day the transportation tasks consisted of wrapping the units to be transported and placing the prototype on the top of the transportable table, as shown in the figure below.



Figure 7: Transportation activities of the SIPS prototype in the first day.

In the second day, with improved weather conditions the units were transported to the school as shown in figure below.



Figure 8: Transportation activities of the SIPS prototype in the second day from INL to school

The VOC prototype was transported back to INL premises on the 30th of March 2026.

Space characterization

The prototype was deployed in the library of the school. The room is located at the entrance of the main building of the school. This is a multifunction room used for classes through the week, ad-hoc meetings, and activities after teaching hours (4PM) used by students with ages from 6 to 12 years old.

The room has a wood floor, covered with large propylene carpets, 2 windows and 4 doors. The chairs are made of polypropylene, and the plant is made of plastic. There is a screen used for classes, a metallic cabinet for storing students' laptops and multiple bookshelves. The ventilation is manual and there is no heating. The room is cleaned in the mornings and painted on a need basis, with no predefined schedule.



Figure 9: View of the room where the prototype was deployed.

Troubleshooting critical risks during installation/first weeks of prototype at the school

During the first weeks of the deployment of the prototype at the school, the INL WP4 team faced a couple of unexpected issues that required troubleshooting and delayed the initiation of the validation, listed in the table below.

Table 5 Troubleshooting critical issues during installation/first weeks of prototype at the school

Critical Issue	Influence on VOC prototype	Mitigation Action	Result
Power cuts	Constant reinitiation of laser and PC	The power cuts were related to storms and/or electrical issues related to school. Installation of an UPS unit that could solve short time (~few seconds-minutes) power cuts	Solved
E0609 Error 	Laser was not operational	The external room temperature was ca. 12°C when the error occurred. When the room temperature reached 15°C the laser went operational; the next couple of days the laser module was left on stand-by mode	Solved

This two not foreseen critical issues delayed the initiation of the validation of the prototype at the school environment. However, those represented for the INL WP4 team knowledge acquisition for further engineering enhancements of the prototype aiming field deployment.

Photoionization signal acquisition

Volatile Organic Compounds

Taking in account D4.1, the VOCs validated in laboratory (BTEX group, reported in this manuscript <https://doi.org/10.1016/j.eti.2026.104895>) and the engineering features of the SIPS prototype, the INL WP4 team selected for detection at the field eight VOCs: benzene, toluene, ethylbenzene and ortho and para-Xylene, styrene, limonene and naphthalene. Limonene was considered due to be a widely used chemical in cleaning and other daily products.

Table 6 VOCs: properties and parameters. Ionisation Potentials and pump wavelengths used.

VOC	$E_{IP}(eV)$	$\lambda_{IP}(nm)$	$\lambda_{VUV-H}(nm)$	$\lambda_{VUV-L}(nm)$
Benzene	9.24	134.2	401.7	402.6
Toluene	8.83	140.4	420.3	421.2
Ethylbenzene	8.77	141.4	423.3	424.2
<i>o</i> -Xylene	8.56	144.9	433.8	434.7
Styrene	8.464	146.5	438.6	439.5
<i>p</i> -Xylene	8.44	146.9	439.8	440.7
Limonene	8.3	149.4	447.3	448.2
Naphthalene	8.144	152.2	455.82	456.7

Routine photoionization signal acquisition

The design of the routine for photoionization signal acquisition enables the attribution of currents detected to a photoionization process. Since we are dealing with volumetric gas, fluxes stabilization periods are incorporated in the protocol. A nitrogen background flow of 200 mL/min was maintained through the data acquisition. Signal detection occurred at normal temperature and pressure (NTP) and applying a bias voltage of 50 V to create a driving electric field for an enhanced collection of the generated photoionisation current.

A measurement loop consisted of:

- 1) Firstly, there was a stabilization period of 360 s with the air collection pump already switch on.
 - a. The video file ([video 1](#)) shows this initial stage.
- 2) Subsequently, the VUV laser wavelength was automatically alternated twice between a pump wavelength respectively above (λ_{VUV-H}) and below (λ_{VUV-L}) the wavelength derived from the ionisation potential (λ_{IP}) of a given compound while the air matrix flowing into the ionisation chamber. Each measurement took 60s. The measurements were done sequentially from the lowest ionization potential (naphthalene 8.144 eV) to the highest ionization potential (benzene 9.24 eV), in accordance with the Table above.
 - a. The video file ([video 2](#)) shows transition of the initial stabilization period of 360 s, to the first wavelength at 456.7 nm ($\lambda_{VUV-L}(nm)$ of naphthalene).
 - b. The video file ([video 3](#)) shows the signal acquisition at 455.8 nm ($\lambda_{VUV-H}(nm)$ of naphthalene) and the change to 448.2 nm ($\lambda_{VUV-L}(nm)$ of limonene).
- 3) The loop measuring the 8 VOCs, 16 wavelengths was iterated 22x, with waiting periods of 120 s between loops.
- 4) Finally, at the end of loop twenty-two there was a waiting period of 360s.



To compare the results obtained with the VOC prototype, we performed simultaneously active sampling with activated carbon sorbent tubes. The flow rate chosen was the same as the VOC prototype: 200 mL/min. Air collection was done at near the inlet of the VOC prototype, at the same time of the VOC prototype acquisition. At least fifteen samples were acquired in these conditions.

Table 7 Required materials for air measurements - chemical parameters

Samples acquired were sent for VOC analysis at KU Leuven partner. The composition of the adsorbed VOCs on the activated carbon of the sorbent tubes will be done by the gold standard analytical technique Gas Chromatography with flame ionisation detection (GC-FID).

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Physical parameters like CO₂ level, temperature and humidity were collected on a 24h basis with a SwitchBot Meter Pro (CO₂ Monitor). The main goal was to correlate the CO₂ level with the VOCs detected in the room. The monitor was placed to the top of the VOC prototype.

Results

Results obtained with the VOC prototype and the comparative method are under processing at the date of deliver of this report. These will be reported at D4.6.

3 TU/e Ultrafine Particle (UFP) Sensor

3.1 Overview and Rationale

The goal of the TU/e contribution to WP4 is to develop a novel UFP sensor capable of detecting and counting individual ultrafine particles (diameter < 100 nm) in indoor air. Rather than relying on conventional condensation particle counters (CPCs) or optical particle counters (OPCs)—which are either too expensive, too bulky, or insufficiently sensitive for sub-100 nm particles—TU/e has pursued a fundamentally different approach based on fiber-tip photonic crystal cavities.

The key insight driving the TU/e approach is that nanoparticles in close proximity to a photonic crystal cavity cause a measurable shift in the cavity's optical resonance wavelength. By monitoring this shift in real time, it is possible to detect individual particles as they interact with the sensor surface. This has been demonstrated under controlled laboratory conditions, as reported in D4.3 and D4.4.

However, a critical challenge identified during the development (Risk R2, as reported in the D4.5 delay justification) is that the fiber-tip sensors operate most effectively in liquid rather than directly in air. To address this fundamental constraint, the TU/e team developed a three-stage approach that bridges the gap between airborne particles and liquid-phase detection, all to be integrated on a single printed circuit board (PCB). The three stages are currently being developed and tested separately, with PCB integration as the target end state.

3.2 Three-Stage Integrated Approach

The integrated UFP sensor prototype consists of three functional stages, each addressing a specific challenge in the detection chain:

Stage 1: Capture of UFPs in a Liquid Droplet

The first stage addresses the challenge of transferring airborne ultrafine particles into a liquid medium suitable for optical detection. Two capture mechanisms have been investigated: inertial impaction and electrostatic delivery.

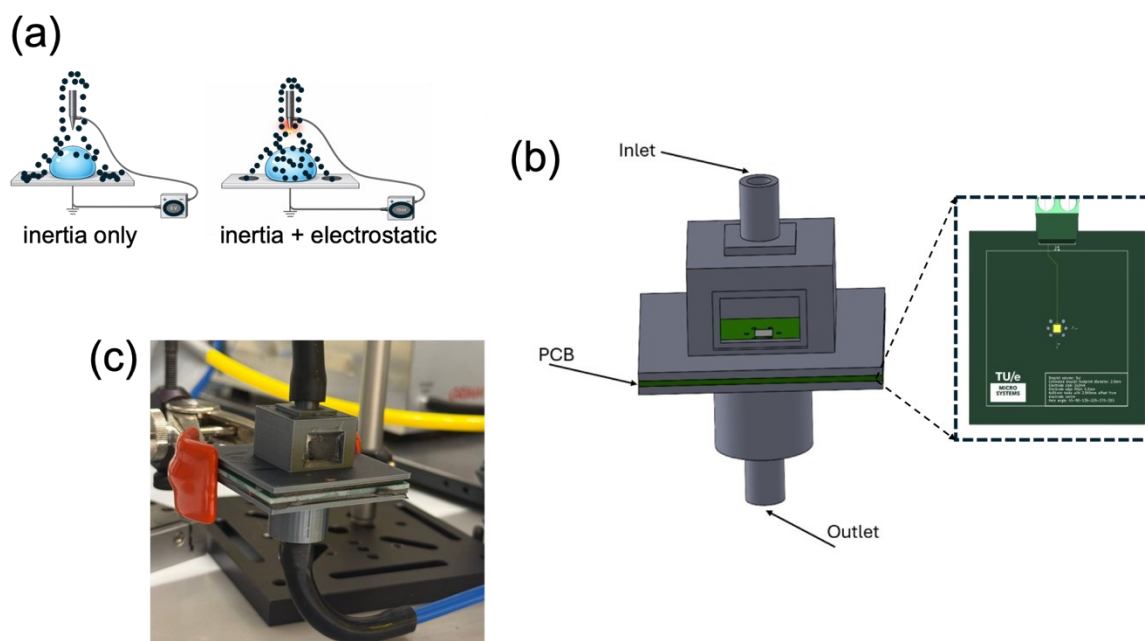


Figure 11: Capture of UFPs in a liquid droplet. (a) schematic of particle capture in an impactor by inertial forces only and by a combination of inertial and electrostatic forces. (b) Schematic design of impactor, where the bottom plate consists of a printed circuit board (PCB) with through-holes that act as air outlets. The close-up shows the CAD design of a corresponding PCB used in our experiments. (c) Photograph of one of our impactor prototypes in the lab.

Inertial capture. In this approach, an air sampling inlet draws ambient air through a defined flow path, directing particles toward a small liquid droplet positioned in the airstream. Particles are captured through impaction and diffusion. While this mechanism has been successfully demonstrated as a proof of principle, experiments revealed that inertial forces alone do not provide sufficient capture efficiency for the target UFP size range. Because ultrafine particles have very low inertia, they tend to follow the air streamlines rather than impacting the droplet surface. To achieve detectable particle concentrations within the droplet, the droplet must be exposed to the airflow for extended periods of time—significantly longer than initially anticipated. This limits the time resolution of the measurement and presents a challenge for practical deployment.

Electrostatic delivery. To overcome the efficiency limitations of inertial capture, the preferred approach is to charge the airborne particles and use an electric field to direct them into the droplet. This electrostatic delivery method can dramatically increase capture efficiency, particularly for sub-100 nm particles. However, the implementation of this approach required a high-voltage laboratory setup, which was delayed due to the need to implement and comply with institutional safety regulations for high-voltage equipment. At the time of writing, this setup is being commissioned and first experiments are underway.

Despite these challenges, a first proof of principle of the complete detection chain was achieved: UFPs were captured via inertial impaction into a liquid droplet, the droplet was manually transferred to the fiber-tip optical detection system, and individual particle detection events were recorded. From the measured particle count rate, the concentration of particles in the droplet can be calculated, confirming that the sensing concept is viable.

Stage 2: Transport of Droplet via EWOD

The second stage employs electrowetting-on-dielectric (EWOD) technology to transport the particle-laden droplet from the capture zone to the optical detection zone. EWOD enables precise, programmable manipulation of discrete droplets on a planar surface by applying voltage sequences to an array of electrodes. This digital microfluidic approach offers several advantages over conventional channel-based microfluidics: it eliminates the need for external pumps and tubing, reduces dead volume, and enables flexible routing of droplets. The EWOD actuation is controlled electronically, making the system compatible with automated, unattended operation—a key requirement for eventual field deployment.

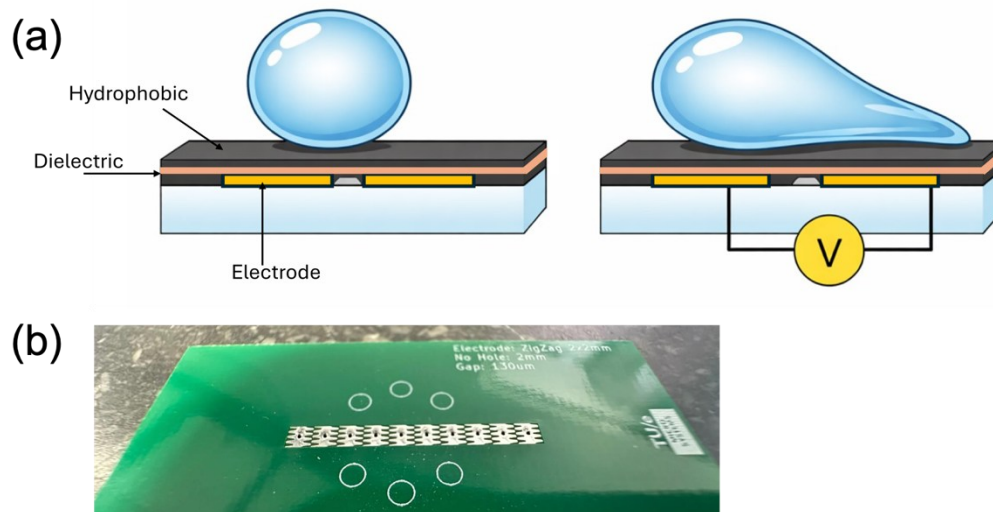


Figure 12: Transport of droplet by electrowetting on dielectric (EWOD) on a printed circuit board (PCB). (a) Schematic of EWOD, left without actuation the droplet stays in a fixed position; when a voltage is applied to the electrodes (right image), the droplet moves towards the high-voltage electrode as a result of electrowetting effects. (b) Photograph of one of the test PCBs designed to test droplet manipulation in our system.

EWOD actuation has been successfully demonstrated in the laboratory on glass-based devices, confirming the viability of the droplet transport concept. However, transferring this capability to PCB substrates has proven more challenging than anticipated. The copper electrodes on a PCB are several hundred micrometers thick, creating steps and surface roughness that interfere with droplet transport. Additionally, achieving sufficient hydrophobicity on the PCB surface—even after coating with SU-8 photoresist and Aquapel for wettability control—has been difficult. These surface quality issues can prevent reliable droplet actuation, which is essential for reproducible operation.

Several mitigation strategies are currently being pursued in parallel: sourcing PCBs from alternative suppliers with tighter surface tolerances, developing methods to fill the gaps around electrodes to achieve a flatter surface topography, and testing alternative surface treatment protocols. An additional setback is that the parylene coater—which would provide a high-quality conformal dielectric and hydrophobic coating—is currently not operational and repairs are expected to take several more weeks.

Stage 3: Detection of UFPs Using Fiber-Tip Optical Sensor

The third and final stage is the optical detection of individual ultrafine particles using a fiber-tip photonic crystal cavity (PhCC) sensor (Figure 4.a). The sensor consists of a photonic crystal nanostructure fabricated on the tip of an optical fiber. When a particle enters the evanescent field of the cavity, it perturbs the resonance condition, causing a measurable shift in the resonant wavelength (Figure 4.b).

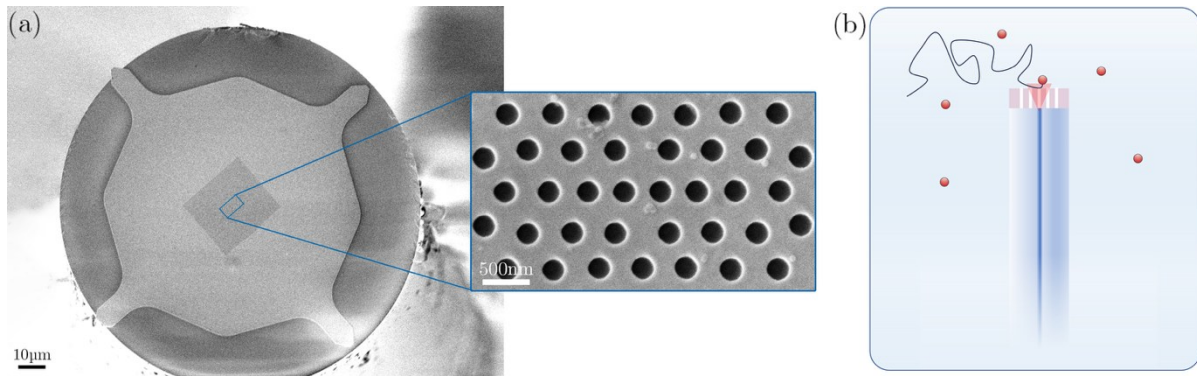


Figure 13: Fiber-tip optical sensor. a) Scanning Electron Microscope Image of the fiber-tip sensor. Inset: Zoom in on the detection area. b) Schematic of particles entering the detection area.

The fiber is connected to a wavelength interrogator (Hyperion SI255) that continuously sweeps through the spectral range of 1460–1620 nm, or a tuneable laser tuned at the side of the PhCC resonance. The analysis of the signal reflected from the fiber enables live tracking of the resonant wavelength. Sharp peaks in the tracked wavelength (Figure 5.b) correspond to individual particle detection events, as demonstrated in D4.4.

The key advantage of this detection method is its sensitivity to particles well below 100 nm in diameter—a size range that is particularly challenging for conventional optical counters and particularly relevant to health effects associated with indoor air pollution.

Experimental results. UFP detection has been successfully demonstrated for a range of particle sizes, from 500 nm down to 50 nm in diameter, at concentrations in the range 10^8 - 10^{11} particles per cm^3 . These experiments confirm that the fiber-tip PhCC sensor is capable of detecting particles well within the ultrafine range that is most relevant to indoor air quality and health.

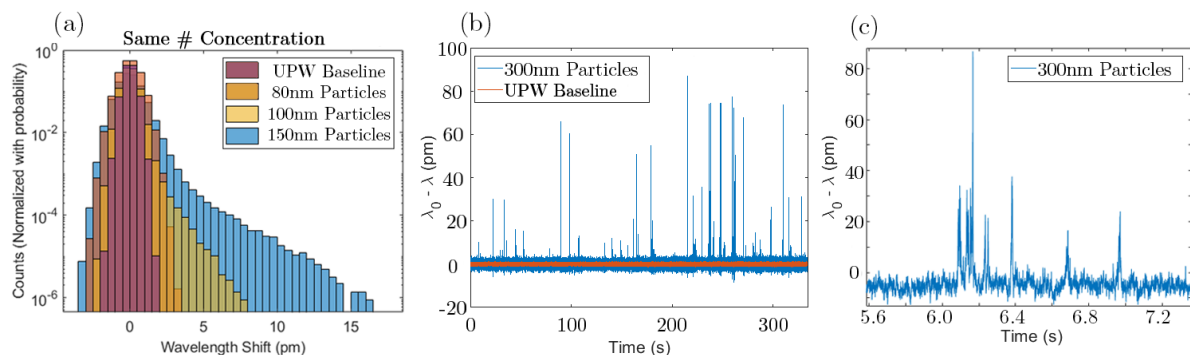


Figure 14: Detected resonant wavelength signals and analysis. (a) Histograms of detected wavelength shifts for different particle sizes (80 nm, 100 nm, 150 nm diameter) at equal particle number concentration; the histogram for ultrapure water (UPW) is also shown as a baseline, reflecting inherent detector noise not related to UFPs. (b) Example of detected shift in the resonant wavelength as a function of time for 300 nm particles. (c) Wavelength shift as a function of time for 300 nm particles, focusing in on single detection events.

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A major current focus is the development of improved data analysis techniques to extract information on particle size and concentration from the measured time traces. In first instance, the frequency of the shifts is observed to change depending on the concentration. The measured distribution of shifts depends on both particle size and concentration. Additionally, the temporal dynamics should carry information on the diffusion rate of particles, and therefore on their size, as these influence the characteristic duration of a detection event (the time a particle spends near the sensor surface). Combining this information in a multiparameter estimation model could provide simultaneous size and concentration measurements—a significant advantage over many existing UFP detection methods. To gather a better understanding of these dependences, systematic measurements as a function of size and concentration have been realized, and Brownian Dynamics (BD) simulations are being developed. This experimental and synthetic data will be used to train and test prediction models for size and concentration.

3.3 Integration on a Single PCB

The current target architecture for the UFP sensor is to integrate all three stages—particle capture, EWOD droplet transport, and fiber-tip optical detection—on a single printed circuit board. In this design, the PCB serves simultaneously as the structural substrate, the EWOD electrode array, the fluidic pathway, and the mounting platform for the fiber-tip sensor.

At the current stage of development, the three functional stages are being developed and tested separately. Individual stages have been demonstrated on dedicated test setups (glass-based EWOD devices for Stage 2, separate fiber-tip detection setups for Stage 3, and standalone capture experiments on a PCB for Stage 1). PCB prototypes have been fabricated and are being used to develop the EWOD actuation on PCB substrates, but full-on PCB integration of all three stages has not yet been achieved. The main obstacles are related to EWOD actuation on PCB substrates (see Section 2.2, Stage 2) and the commissioning of the electrostatic capture setup (see Section 2.2, Stage 1).

Once achieved, this integrated design will represent a significant step toward miniaturization and eventual field deployment, reducing the number of external components, simplifying assembly, and creating a pathway toward a compact, low-cost, self-contained sensor module.

3.4 Current Status and Path to Field Deployment

The TU/e team acknowledges that the UFP sensor prototype has not yet reached the stage of a fully operational field-deployed instrument. The reasons for this are twofold:

- The late integration of TU/e into the consortium and the subsequent late start of the two PhD projects (Hasan Yalcinoglu started Nov. 2023, and Mostafa Taghipour started Apr. 2024) caused an 18–24 month delay relative to the original schedule.
- The adoption of a fundamentally new sensing concept—fiber-tip photonic crystal cavities—required substantial fundamental research before system integration could begin. While this approach offers breakthrough sensitivity, it inherently carries higher development risk and longer lead times than incremental improvements to existing sensor technologies.

Additionally, as described in Section 2.2, the particle capture stage (Stage 1) encountered practical challenges that further delayed system-level integration:

- The electrostatic delivery approach, which is essential for efficient capture of sub-100 nm particles, required a high-voltage laboratory setup. Implementation was delayed due to the time needed to comply with institutional safety regulations for high-voltage equipment.

- Inertial impaction alone proved insufficiently efficient for the target particle size range, requiring prolonged droplet exposure times to reach detectable concentrations.

Notwithstanding these constraints, significant progress has been made:

- Single-particle detection has been demonstrated in controlled laboratory conditions (D4.3, D4.4).
- The three-stage approach (capture, EWOD transport, fiber-tip detection) has been designed, and the individual stages have been validated.
- A PCB design accommodating all three stages has been developed; individual stages are currently being tested separately, with full on-PCB integration as the next milestone.
- Risk R1 (particles needing to stick to the sensor surface) has been resolved: particles can be detected as they move in and out of the detection region without irreversible attachment.
- A complete proof-of-principle detection chain has been demonstrated: inertial capture of UFPs into a droplet, manual transfer to the detection system, and successful single-particle detection using the fiber-tip optical sensor.

The remaining challenges—most critically, achieving sufficient capture efficiency through electrostatic delivery (Risk R3) and ensuring reliable sensitivity under ambient conditions (Risk R2)—are being addressed in the ongoing PhD research. The high-voltage electrostatic capture setup is currently being commissioned. Task 4.4 (Sensor Testing and Validation) will be delivered in the Final Validation Report (D4.6).

4 Conclusions

This deliverable reports on the status of the sensor prototypes developed in WP4 toward field deployment.

4.1 VOC Sensor (INL)

The deployment of the VOC sensor at a school required software, mechanical, electronical and optical engineering enhancements. After completion was possible to deploy the VOC prototype at a local school in Braga, Portugal.

4.2 UFP Sensor (TU/e)

The TU/e UFP sensor has progressed from proof-of-concept single-particle detection (reported in D4.3 and D4.4) to a three-stage sensing architecture with individually validated stages and a first successful demonstration of the complete detection chain—from airborne particle capture through to quantitative optical detection. Particle detection has been demonstrated for sizes ranging from 500 nm down to 50 nm. The three stages—particle capture in a liquid droplet, EWOD-based droplet transport, and fiber-tip photonic crystal cavity detection—are being developed and tested separately, with integration on a single PCB as the target end state.

The consortium acknowledges that, despite the rescheduling of MS8 from M44 to M47, the UFP sensor has not reached full field-deployment readiness at the time of this deliverable. The combination of the late start (TU/e joining approximately one year after project launch, with PhD students starting approximately two years in), the adoption of a high-risk/high-reward sensing concept, and practical challenges across all three stages—delayed commissioning of electrostatic capture due to safety regulations, difficulties with EWOD actuation on PCB substrates due to surface roughness and hydrophobicity issues, and the need for advanced data analysis techniques for quantitative concentration extraction—have collectively prevented reaching a field-deployable prototype within the revised timeline. Nevertheless, the proof-of-principle demonstration confirms the viability of the approach, and the two ongoing PhD projects will continue to advance the technology, targeting the critical remaining milestones: reliable EWOD actuation on PCB, electrostatic particle capture, and validated concentration extraction algorithms.

It is important to note that this delay does not critically affect other LEARN deliverables or milestones. No other work packages depend directly on the TU/e UFP sensor for their activities. The originally foreseen collaboration with WP6 (Task 6.3) has been adjusted: Mann+Hummel employs a commercial UFP sensor for their validation tests, ensuring WP6 progress is not compromised.

4.3 Outlook

INL has completed the development and field testing of the VOC sensor as reported in this deliverable. A comprehensive documentation of the testing and validation outcomes for the VOC sensor will be provided in the Final Validation Report (D4.6).

For TU/e, Task 4.4 (Sensor Testing and Validation) remains active until the end of the project. Even after the official completion of LEARN, the two PhD students will continue to work on this topic for almost two years, ensuring that the fundamental research investment made within the project will be carried to maturity. If the anticipated six-month extension is granted, TU/e expects to be able to achieve field testing of a prototype UFP sensor within the extended LEARN project period. TU/e will include any progress on field testing of the UFP sensor prototype, along with a documentation of the complete validation outcomes, in the Final Validation Report (D4.6).