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Research and Innovation Action

European Sensor System for CBRN Applications (EU-SENSE)

D1.5 Final Project Report

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Executive summary

The following is the final project report of the EU-SENSE project. This report summarizes the work performed within the span of the project. This is the third and last of the reports (first two being the Annual Reports) which were set to be delivered during the duration of the project.

The report details the methodology used in the project's research as well as the overall development made in all work packages specified in the project proposal. The Project Management WP consisting of general overseeing actions, Consortium Meetings and list of the WP’s deliverables is presented. Then, the Operational Needs and Requirements WP is detailed, divided into descriptions of background and context, concept with approach, and collection of user requirements as well as the development of suite of scenarios and requirements prioritization. In WP3, the general system architecture and its evolution during the project is depicted. Next, the EU-SENSE sensor node development being the essence of WP4 is presented as well as the supporting it machine learning of the environmental noise algorithms that are the outcome of WP5. The following is WP6 – Situational Awareness that consists of, i.a., three main tools of the system that are Source Estimation, Hazard Prediction and Situational Awareness Tool. Next is WP7 describing Integration and Validation of the developed system, detailing the engineering and validations approaches with their results and outcomes. Last two WPs illustrate the training and demonstration of the system as well as its dissemination and exploitation. Moreover, the Report presents the foreseen and unforeseen implementation risks with actions taken to mitigate them, followed by lessons learned from the project and its development

It is also critical to emphasize that the EU-SENSE initiative was impacted by the coronavirus pandemic. The pandemic's primary and immediate impact was the suspension of measurement sessions, as consortium partners were directed to operate remotely and laboratories prioritized testing for the healthcare sector. In general, the pandemic hampered the speed of work on the project, which resulted in additional 6 months given to finalize and deliver all contracted works.

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Abbreviations

AEGL	Acute Exposure Guideline Levels
AOI	Area of Interest
API	Application Programming Interface
CBRN	Chemical, Biological, Radiological and Nuclear (hazards)
D	Deliverable
DE	Dispersion Engine
EC	Electrochemical Cell
ENLT	Environmental Noise Learning Tool
EPA	Environmental Protection Agency
FPD	Flame Photometric Detector
GUI	Graphical User Interface
HP	Hazard Prediction
IFAFRI	International Forum to Advance First Responder Innovation
IMS	Ion Mobility Spectrometry
KPP	Key Performance Parameters
MO	Metal Oxide
NSC	Network of Sensors Controller
PID	Photoionization Detector
SA	Situational Awareness
SLE	Source Location Estimation
WP	Work Package

1 Introduction

The European Sensor System for CBRN Application (EU-SENSE) project was funded by European Commission under Grant Agreement no. 787031. Though the project was originally scheduled for 36 months, the outbreak of the COVID-19 pandemic delayed certain areas of the project. To mitigate the risk and deliver all contracted works, the consortium applied for the project extension, which gave the project additional 6 months.

The project emerged as a response to capability gaps identified by ENCIRCLE catalogue[1] and International Forum to Advance First Responder Innovation (IFAFRI)[2] in their study. At the proposal stage, the consortium identified three high-level objectives, which have been achieved in the EU-SENSE project. These objectives include the following:

- High-Level Objective 1 – to contribute to better situational awareness of the CBRNe practitioners through the development of a novel network of chemical sensors, which will provide a technological solution to relevant gaps presented in the ENCIRCLE catalogue.
- High-Level Objective 2 – to improve the detection capabilities of the novel network of chemical sensors through the use of machine learning algorithms to reduce the impact of environmental noise and the application of contaminant dispersion models.
- High-Level Objective 3 – to showcase the usability of the EU-SENSE network to CBRNe practitioners in order to validate the system and to maximise its exploitation potential. The objective also entails the preparation of the training sessions with CBRNe practitioners in relevant conditions.

To deliver the above listed high-level objectives, the consortium members conducted research and development works on combining different detection technologies within a single node to improve the spectrum of detectable substances as well as investigate if the broader set of data can be used to limit the ratio of false-positive/negative alarms generated by the system. To achieve this, also research on environmental noise and its impact on sensor readouts was performed as well as data fusion algorithms for classification, identification, and concentration estimation.

Moreover, it has been essential to improve the situational awareness of first responders in the field. Therefore, the work focused on the design and development of computational tools such as Source Location Estimation and Hazard Prediction, which are designed to estimate the source of the detected hazard and predict its most probable dispersion route. The results of these two tools and all other data generated and processed by the network are displayed in the Situational Awareness Tool, which is the main access point.

Throughout the project's lifetime, the consortium showcased the project concept and achieved results on many conferences, fairs, and exhibitions devoted to CBRN protection. The frequent communication activities, even though limited by the COVID-19 pandemic, helped to generate a good awareness about the EU-SENSE project across different communities in Europe including academic units, end-users, and stakeholders. The integrated and operational EU-SENSE system was showcased by the consortium to invited guests during the final demonstration of the project held on 6-7 October 2021 in Warsaw and Nowy Dwór Mazowiecki (Poland).

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[1] European CBRN Innovation for the Market Cluster. (URL: https://encircle-cbrn.eu/catalogue)

[2] International Forum to Advance First Responder Innovation (URL: https://www.internationalresponderforum.org)

1.1 Document scope

The deliverable is composed of the following sections:

- **Section 2** – the section touches on the research methodology applied in the project.
- **Section 3** – the section presents milestones and the overall project progress performed in all work packages foreseen in the project proposal.
- **Section 4** – summarises the risks encountered in the project. The division is made between those risks already identified at the proposal stage and unforeseen risks identified during the project realisation.
- **Section 5** – presents the lessons learned in the project and summarises the issues that should be taken into consideration while addressing similar research subjects.
- **Section 6** – presents the main conclusions of the project.

2 Project methodology

Due to the size of the endeavour that the EU-SENSE project has been, the consortium has decided to utilise a number of research methodologies in order to be able to benefit from the best traits of each one.

In order to provide the best results from the technological point of view, the consortium has chosen to work in an iterative manner, which translated to a number of prototypes of the components being created along the course of the project. The best example of that approach is the development process of the EU-SENSE Heterogeneous Sensor Node presented in Table 1. The table shows exactly how each generation of the component offered a broader range of functionalities and ultimately led to the complete solution that has been presented at the final demonstration of the project.

Furthermore, as a way to make sure that the final results of the project will have a practical application in real-life conditions, the EU-SENSE consortium has decided to put a large amount of focus on maintaining a user-oriented development process. This approach could have been observed from the very first stages of the project as the consortium itself was built with the involvement of end-users – SGSP and PSNI. Their role was to advise on developed solutions from a practitioner’s point of view and test them in the course of the project providing invaluable feedback to the research team. Furthermore, the project was supported by the Stakeholder Group that included a number of end-user representatives and, at the very beginning of the project, the EU-SENSE consortium has held a Stakeholder Workshop, during which the ideas for the project have been presented in order to gather feedback from the potential target group of the developed solutions. Finally, the project’s proposal has been created with the needs of actual end-users in mind (listed in the IFAFRI study), as well as the gaps on the CBRN safety market (presented in the ENCIRCLE catalogue).

Additionally, the EU-SENSE consortium has performed numerous measurement sessions, both in outdoor and indoor conditions. These sessions were first held in controlled conditions in facilities of the project partners, and then performed in various natural conditions that exposed the components to the environmental noise (i.e. car fumes from a nearby road, etc.). Those measurements have provided the development team with plenty of data and insight that allowed to create a basis to develop the sensor model, Environmental Noise Learning Tool, and the data fusion algorithms. The additional benefit of those sessions was the opportunity to test the components and gather feedback on their performance in both lab and outdoor conditions.

The use of abovementioned methodologies allowed the EU-SENSE consortium to develop a solution that could have a practical application in real-life conditions in an efficient and controlled manner.

3 Project summary

3.1 Milestones

At the proposal stage of the project, the consortium has established a set of milestones to be met in order to track the progress made. The table below contain all of the milestones that have been initially set by the partners.

Milestone number	Milestone title	WP number	Means of verification
MS1	Requirements for the system	WP2	Use-cases adapted, user requirements collected and key performance parameters defined.
MS2	Technical Requirements and the first version of the architecture	WP3	Technical requirements for the components have been specified and first version of the architecture have been released.
MS3	Interfaces and data model	WP3	A second version of the architecture has been delivered. Interfaces and data model have been defined and final.
MS4	A prototype of the EUSENSE system	WP7	The first, prototype version of the system have been provided. Measurements can be acquired from sensors by the system.
MS5	Core functionalities implemented	WP7	The core functionalities of the system have been implemented (semi-final versions) and successfully integrated.
MS6	Final version of the system	WP7	The system is successfully integrated, validated and is ready for the demonstration.
MS7	Final Demonstration	WP8	The system has been successfully demonstrated.

All of the milestones presented above have been met in the course of the project's lifetime providing important reference points for the progress of the research and development process performed by the EU-SENSE consortium. The following sections summarise the overall progress of the EU-SENSE project in each work package.

3.2 WP1 Project Management

In general, work package 1 since the very start focused on maintaining good communication within the consortium as well as management and monitoring of the project. To provide good communication, the coordinator ensured a shared mailing list and regular online and physical meetings discussing progress. Moreover, given that some EU-SENSE deliverables have been marked as EU-RESTRICTED, encryption software accepted by European Commission was provided to all partners dealing with said information (i.e. ZED! 4.0).

Throughout the project lifetime, the consortium had several progress meetings including:

- Consortium Meeting (Project Kick-off), 28-29.05.2018, Warsaw, Poland
- Consortium Meeting, 14-15.11.2018, Bonn, Germany
- Consortium Meeting, 16-17.05.2019, Poznan, Poland
- 1st Review Meeting, 3.12.2019, Brussels, Belgium
- Consortium Meeting, 9-10.03.2020, Belfast, United Kingdom

The physical meetings were paused after the first travel restrictions were imposed as an aftermath of the COVID-19 pandemic.

An essential part of the WP1 work has been the quality assurance and technical management of the project. Each deliverable underwent a technical quality check to make sure the project results are properly reported to the European Commission.

Work package 1 also generated many deliverables, which include the following:

- D1.1 Project Handbook
- D1.2 Project Website
- D1.3 Annual Report (I)
- D1.4 Annual Report (II)
- D1.5 Final Project Report
- D1.6 Report on the distribution of the pre-financing

The EU-SENSE project also underwent a periodic review by the Project Officer and Project reviewers. The review meeting was held on 3.12.2019 in Brussels. The overall progress examined by the PO and reviewers was satisfying and all deliverables produced in P1 were accepted. The reviewers, however, pointed to the need to tackle the measurements campaign more efficiently so that a satisfactory dataset is generated. To prove the measurement campaign will be properly tackled, the consortium prepared a contingency plan, which was ultimately accepted by the Project Officer and the reviewers.

The proposed plan was, unfortunately, interrupted by the spread of the COVID-19 pandemic across Europe and the implementation of restrictions in most of the EU countries. This risk that emerged as a result of the pandemic was mitigated by the measures described in the formal amendment [1] of the project. Consequently, the project duration was extended by 6 months to deliver the full scope of the project with very good quality.

3.3 WP2 Operational Needs and Requirements

3.3.1 Background and Context

Protecting citizens, institutions, infrastructures, and assets is one of the four key pillars of the EU's Counter-Terrorism Strategy [2]. However, recent developments in Syria, Malaysia, and United Kingdom give good reasons to believe that the hazard posed by chemical agents, including chemical warfare agents, remains high and is evolving. Although numerous activities have been undertaken by the EU and its Member States to improve the ability to prevent and protect its citizens against chemical, biological, radiological, nuclear, and explosives (CBRNe) incidents, it is still important that detection and mitigation of CBRNe risks at the EU level continue to be developed.

In 2014, a new CBRNe Agenda was set out to focus on key priorities to be addressed at the EU level [3]. The new CBRNe Agenda states that the following issues must be addressed in any effective mitigation strategy to improve the detection of risks and promote awareness-raising, training sessions, and exercises amongst others:

- The effectiveness and performance of existing equipment and processes;
- New threat substances;
- New modus operandi for attacks;
- New concealment methods to attempt to by-pass security controls;
- New attack targets (soft targets, critical infrastructures, public areas, non-aviation areas).

Better detection was especially highlighted in the new CBRNe Agenda because fast detection of an incident is paramount to safeguard the life and health of the population. The ability to rapidly detect CBRNe incidents equates to faster response times, reduced-hazard exposure, and more efficient use of limited resources. This requires building robust situational awareness for first responders and crisis management in (near) real-time.

Although significant progress has been made in recent years, there are, however, still substantial shortcomings in detection technologies in the different areas of public security. Improved detection was therefore identified as a capability-need in the Catalogue of Technologies published by the ENCIRCLE project (http://encircle-cbrn.eu/), as part of the EU Horizon 2020 RIA call SEC-05-DRS-2016-2017: Chemical, biological, radiological and nuclear (CBRN) cluster part b). Specifically, the catalogue identified the following high-priority gaps and needs related to CBRNe detection:

- "*Insufficient equipment for estimation of contamination, and insufficient training in the use of the equipment. Lack of instant scanning, single or multipurpose detectors, which are fast, sensitive, robust, reliable, affordable, handheld, and which do not disturb business continuity when applied in the prevention or preparedness phase. Needs to detect a large spectrum of detectable agents, and detect degree of hazard and residual, post decon, contamination. Must produce less false positive results*"
- "*Lack of suitable equipment for use with untrained persons. Many of the existing systems do not support simulation and/or training modes, making them difficult to operate for personnel who are not normally involved in CBRNe activities*"

3.3.2 Concept and Approach

The conceptual design of the EU-SENSE system comprises the following three integral aspects:

- Threat Detection
- Situational Awareness
- Training and Simulation

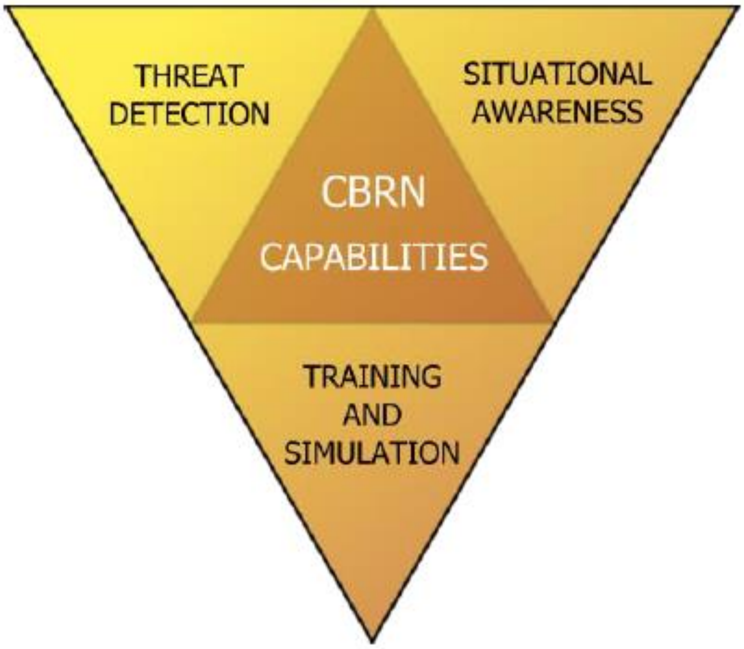

Figure 1 Integral aspects of the EU-SENSE system

These aspects are illustrated in Figure 1. The threat detection part will be comprised of a network of stationary and person-worn sensors for chemical detection supported with novel data-fusion algorithms. Fused data from the network of sensors will feed into the situational awareness tool that will give end-users the ability to simulate the hazard dispersion over the area of interest. The hazard prediction will be comprised of inverse modelling for source estimation and ensemble forward modelling to calculate potentially threatened areas based on uncertainties from the inverse modelling. Lastly, the EU-SENSE system will be composed of a training and simulation module that enables end-users to train on the use of the system and rehearse specific use cases.

3.3.3 Collection of User Requirements

The user requirements collection process has been performed in compliance with established best practices to ensure that the requirements are clear, verifiable, prioritized, consistent, traceable, and unbiased (not favouring a specific solution) [4]. To establish detailed end-user requirements for the EU-SENSE system and its main components, a Stakeholder Workshop was arranged for the EU-SENSE Stakeholder Group at the University of Warsaw, Poland, on 8-9 August 2018. This Stakeholder Workshop fulfilled three purposes: (i) to let the Stakeholder Group familiarize themselves with the proposed technical concept of the EU-SENSE system (Day 1); (ii) provide end-user guidance to the establishment of the suite of scenarios (D2.1) [5] (Day 1); and (iii) collect end-user requirements for the EU-SENSE system (Day 2). Based on EU-SENSE conceptual approach (Figure 1), the following main categories were defined for the system:

- A chemical detection system (consisting of stationary and person-worn sensor nodes)
- Network of sensors
- Situational awareness tool
- Training module

Before the Stakeholder Workshop, a questionnaire for the collection of end-user requirements was drafted and refined based on the Consortium Partners' feedback. The questionnaire was comprised of 26 questions where 17 questions addressed the chemical sensor nodes, three questions addressed the network of sensors, three questions addressed the situational awareness tool, two questions addressed the training mode, and the last question addressed aspects not covered by the previous questions.

The Stakeholder Group is an advisory body outside the project management structure, comprised of end-users, industry partners, academia, and subject matter experts closely related to the project scope. The following members constitute the Stakeholder Group:

- Swedish Armed Forces, National CBRN Defence Centre (Sweden)
- VTT - Technical Research Centre of Finland (Finland)
- Norwegian National Unit for CBRNE Medicine (Norway)
- Imperial College London, Institute for Security Science & Technology (United Kingdom)
- CBRNE Ltd (United Kingdom)
- DJChem Chemical Poland S.A. (Poland)
- Hotzone Solutions BV (The Netherlands)
- Brandweer Zuid Limburg (The Netherlands)
- Research for Science, Art. And Technology (RFSAT) Ltd. (United Kingdom)
- Intrepid Minds Ltd (United Kingdom)
- Swedish Civil Contingencies Agency (Sweden)
- Municipal Headquarters of the State Fire Service in Siedlce (Poland)
- County Office Tarnowo Podgórne (Poland)

3.3.4 Suite of scenarios

The EU-SENSE scenario set is composed of two events – a **Mass event scenario** and a **Toxic industrial contamination scenario**. Such scenarios can turn into a huge man-made disaster that affects many people, infrastructures, and environmental elements in a large area. The presented case studies can be located in many places around Europe. The way they are designed gives enough flexibility for the implementation of chemical sensor systems aiming at the achievement of the High-Level Objectives given in Chapter 1. The scenarios can be implemented into demonstration and evaluation processes as well as state foundation in training sessions.

Two different events are taken into consideration. The first deals with a mass event, which is based on the final event of the Great Orchestra of Christmas Charity in Warsaw, Poland. Characteristic aspects of the event reflect general determining factors and challenges that should be faced by CBRN practitioners in case of an object emergency. The second scenario focuses on an incident with toxic industrial contamination. It is related to problems with transportation of hazardous materials (release of chemical agents) occurring during the transportation from chemical plant premises in Poland with potential influence for nearby city habitants.

In both case studies, event description and scenario definition are formulated. Events are described by a short introduction, infrastructure, weather conditions, threats, and story timeline, stating preliminary situational awareness [5]. Each scenario is defined by a set of vignettes. They allow for quasi-cross analysis corresponding with crucial EU-SENSE functionalities:

- Deployment of a stationary network of chemical sensors
- Provision of security units and/or police officers equipped with person-worn sensors
- Collecting sensor measurement from the event area
- Data processing (machine learning)
- Providing real-time on-site information
- Source location estimation
- Hazard prediction
- Safe-zone estimation

These eight perspectives give additional information about scenarios and additional value of the sensors network in terms of supporting CBRN practitioners in correspondence with particular High-Level Objectives.

The Mass event scenario allows to analyse aspects of terrorist attacks that influence CBRN threat and consequences (Figure 2). It is relatively representative and reflects incidents that occurred in (e.g. London (2005), Oslo (2011), Paris (2015), and Brussels (2016) [6][7]. According to the mass event scenario assumptions, the nerve agent Sarin is released by a terrorist located in a residential building situated at Marszałkowska 104/122 Street (in the East direction from the event area, Figure 2).

The timeline is ascribed into two main emergency management phases: preparedness and response. The preparedness phase concerns detection-related actions to be performed before the mass event starts and the threat occurs. During this phase, CBRN-detection is achieved by proper deployment of sensors and by making organizational user-directives in case of emergency. The response phase is initiated by threat identification. When it appears, effective actions should be carried out to rescue people. According to the mass character of the event, information concerning the agent source-location estimation, hazard prediction, and safety zone estimation are immediately required.

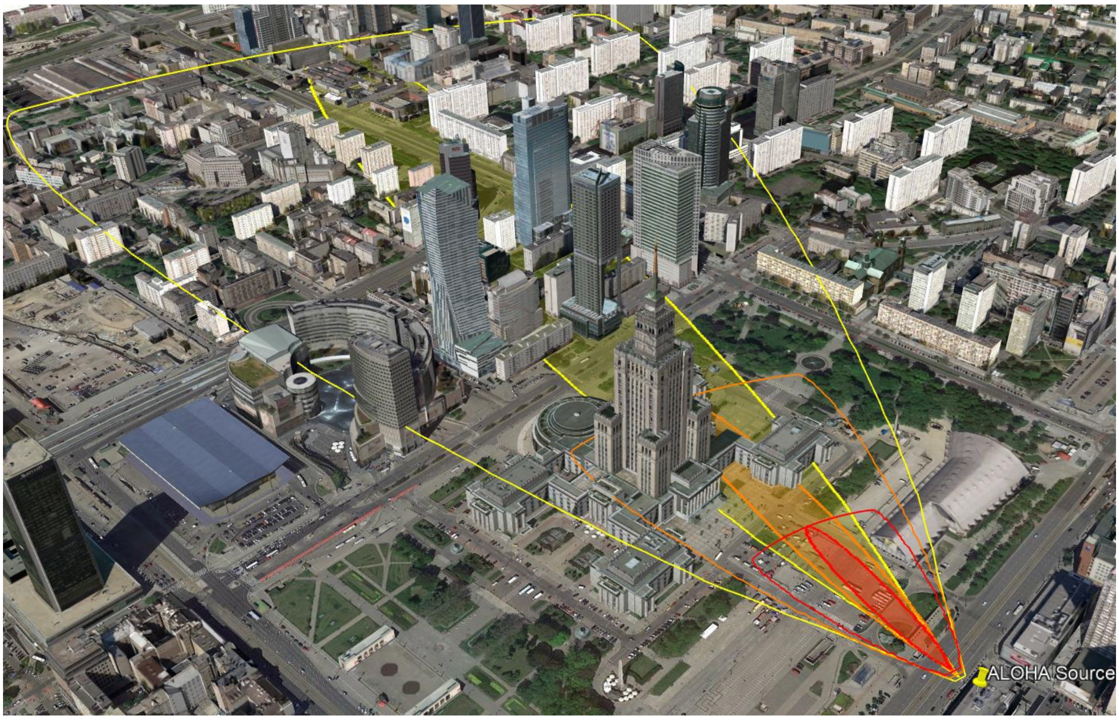

Figure 2 Visualization of potential danger range for Sarin, showing AEGL-3 (red line), AEGL-2 (orange line), and AEGL-1 (yellow line) after 15 minutes

The second scenario describes an accidental release of a toxic industrial chemical during transportation in the chemical plant. In this event, there is no possibility to perform any preparatory actions. The scenario focuses therefore on the response phase, starting from the beginning of the incident (toxic industrial chemical release) when the first responders rely on their experience and information coming from sensors and preliminary predictions.

The scenario plays a role in the identification of challenges and end-users needs in terms of a toxic industrial contamination scenario. This scenario allows for the analysis of a wide spectrum of aspects related to the storage and transport of hazardous materials, especially in urban areas (Figure 3). It is relatively representative since it reflects incidents that occurred in (e.g. in Flix (1996) and Tianjin Binhai (2015) [8][9][10]).

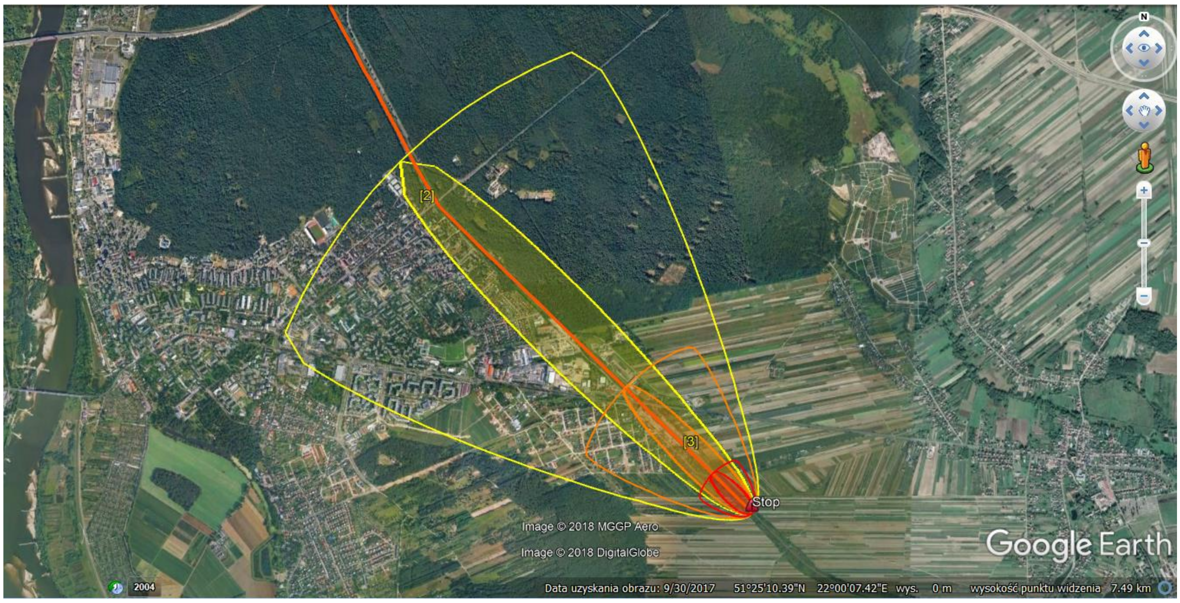

Figure 3 Visualization of potential danger range for ammonia, showing AEGL-3 (red line), AEGL-2 (orange line), and AEGL-1 (yellow line) after 30 minutes

3.3.5 Prioritization and Categorization of the User Requirements

Fast and robust detection of a chemical incident is paramount to safeguard the life and health of the affected population. The ability to rapidly detect such incidents equates to faster response times, reduced-hazard exposure, and more efficient use of limited resources. Although significant progress has been made in recent years, there are still significant shortcomings in chemical detection technologies.

For the work in the EU-SENSE project, a key performance parameter (KPP) is defined as a performance attribute of the system that is considered critical or essential to the development of an effective EU-SENSE system that meets the user requirements for the identified suite of scenarios. The KPPs must be specific and measurable to support an effective test and validation of the EU-SENSE system. The KPPs are expressed in terms of a unique identification number, specification of parameters that reflect measures of performance using a minimum threshold/target goal format, which scenario vignettes and user requirements are covered, and any caveats and comments that are of consideration for the KPP.

A set of key performance parameters (KPPs) for the system was developed, based on the previously established suite of scenarios and collected user requirements [11]. This work resulted in an agreed framework set of KPPs that was used in subsequent design, assessment, and validation tasks.

The following set of key performance parameters was formulated:

1. End users are trained to use the EU-SENSE system
2. Operating time for stationary sensor nodes without maintenance
3. Operating time for person-worn sensors in the hot zone without maintenance
4. The time needed for physical setup of the stationary sensor nodes after being deployed to the scene of interest
5. The time needed for making person-worn sensors ready for use
6. The time needed for machine learning for the chemical detection system when the EU-SENSE system is used in the preparedness phase
7. No disruption of business continuity when the EU-SENSE system is applied in the preparedness phase
8. Instant estimation of hazardous contamination level during incidents involving chemical warfare agents or toxic industrial chemicals
9. Estimation of source location
10. Hazard prediction
11. Estimation of residual, post-decon, contamination level after incidents involving chemical warfare agents or toxic industrial chemicals

Based on the set of KPPs, a total of 42 user requirements for the EU-SENSE system were formulated as part of Task 2.1 [5]. All requirements were prioritized into “shall” and “should” requirements.[3] In addition, all requirements were categorized as “functional” and “non-functional”.[4] The user requirements were presented for the system as a whole and the following four sub-systems:

(i) Chemical detection system

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[3] “Shall” requirements denote requirements that are mandatory whenever the criterion for conformance with the specification requires that there are no deviations. “Should” requirements denote guidelines or recommendations whenever noncompliance with the specification is permissible.

[4] A “functional” requirement denotes any requirement that specifies what the system should do, while a “non-functional” requirement denotes any requirement that specifies how the system performs a certain function.

(ii) Network of sensors

(iii) Situational awareness tool

(iv) Training module

For the system as a whole, the following user requirements were formulated:

- “The EU-SENSE system shall demonstrate improved detection performance compared to the current state-of-the-art detection technologies that are incorporated into the system for the scenarios identified in the EU-SENSE project;”
- “The time needed for the EU-SENSE system to take a decision shall be equally good or improved while at the same time the false alarm rate is reduced, compared to the current state-of-the-art detection technologies that are incorporated into the system for the scenarios identified in the EU-SENSE project.”

Together, the 11 formulated KPPs cover the whole suite of adapted scenarios and 34 out of 42 collected user requirements.

3.4 WP3 System Architecture

Working on system architecture started with a closer analysis of user requirements and key performance parameters defined within WP2. The first significant deliverable was *D3.1 Technical requirements specification* [17], a document which, in principle, was supposed to translate the user requirements into the technical specification of the EU-SENSE system.

The first basic division was the differentiation of EU-SENSE system user classes and their respective privileges in the system. As a result, 4 user classes were defined including technical expert, responder, training expert, and IT administrator. The main user type is the technical expert, who has access to readouts from the system components displayed in the Situational Awareness Tool and has the option to trigger computational tools as well as manually raise/decline alarms. The responder, on the other hand, has access to SA Tool in data preview mode only. The responder view was considered at this stage with the intent to provide responders/commanders deployed in the field ability to access crucial information on the detection status, nodes status as well as source location and hazard prediction visualisations.

An essential step was to filter through user requirements and define the scope of the EU-SENSE system having in mind the budget foreseen for hardware purchase. As a result, the EU-SENSE project was limited to the development of three heterogeneous sensor nodes, which have combined four different chemical detection instruments including AIRSENSE GDA (IMS+PID), AIRSENSE GDA (IMS+EC), TNO SRD sensors (MO detection array), and PROENGIN AP4C (FPD).

The EU-SENSE technical requirements addressed general as well as component-specific requirements. Beginning with general requirements, the consortium first defined the substance detection threshold of the system. Here, a discussion on AEGL-1[5] and AEGL-2 concentration levels was organised to check what is feasible and expected by end-users. The basic distinction between levels 1 and 2 is that the prior requires notification of the public that a potentially harmful substance was detected, which might cause mild health side effects. The latter concentration level, on the other hand, results in irreversible or long-lasting health effects. It was agreed that the system should detect selected substances at the AEGL-1 level and send a notification to the user. In the case of AEGL-2 level detection, the system shall display an alarm notification to the user.

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[5] AEGL – Acute Exposure Guideline Levels – is a set of exposure guidelines to predict how the general public would be affected should they be exposed to a hazardous chemical substance. Three AEGL level are defined within the guidelines. (source: https://response.restoration.noaa.gov/oil-and-chemical-spills/chemical-spills/resources/public-exposure-guidelines.html)

Furthermore, the complexity of CBRN scenarios addressed in D2.1 [5] brought into the foreground the discussion on the operational mode of the system. The scenarios such as mass event attacks or industrial incidents require the EU-SENSE system to work both in preparedness and response phases. The deployment of the system should not, in any way, hinder the overall conduct of the response mission led by first responders. As a result, the EU-SENSE has two distinct modes: preparedness and response, and the system might be deployed from the onset of the mission in any of the two modes. Mode selection is made at the start of the system. The preparedness mode means that the system works in advance of the chemical hazard release (e.g. mass events) and collects environmental noise data. This phase also referred to as pre-learning, is crucial because the system learns the background noise of the environment, filters non-essential signals which could trigger the false alarm, and passes only the anomalies above a certain threshold. However, the detected environmental anomaly may not always mean there is a chemical release/incident. Thus, the consortium decided to define necessary data fusion algorithms, which would determine if the output of the Environmental Noise Learning Tool (i.e. environmental anomaly) is a chemical hazard. For that purpose, it was required that the system should perform classification, identification, and concertation estimation. Though the data fusion block was not addressed nor specified in the project proposal, it became a necessary (and significant) aspect of the system during project realization to achieve the project's high-level objectives. A thorough discussion related to the scope of project design, specifics of data fusion component as well as operational mode were addressed during the dedicated EU-SENSE technical workshop, held in Warsaw on 19-20.02.2019.

Figure 4 EU-SENSE technical workshop, Warsaw, 19-20.02.2019

The defined requirements for the above-mentioned data processing constitute the overall added value of the system and distinguish the EU-SENSE system compared to commercially available systems. To make the system stand out and answer to end-user capability gaps, it was also a priority to define the other functionalities leading to improved situational awareness. As a general tool for situational view for the end-users, the Situational Awareness Tool (SA) was defined. The end-users expected to have a tool, which combines and visualises the processed data from all network assets[6] and processing/computational tools. While developing the central user access point (SA Tool), it was critical for the developers not to overload the main view with the abundance of information, which could be only a detriment to the situational awareness and operation of the tool. Consequently, the tool offers a clear view of the area of interest (based on OpenStreetMap API), icons visualising the position of sensor nodes, a detailed configuration menu comprising information on sensor nodes configuration, their health, etc. More information on SA Tool is presented in section 3.7.

The proposal identified also functionalities of source location estimation and hazard prediction. During consultations with end-users, these two functionalities were highly prioritized and deemed 'must-have' functionalities of the system. The end users justified high priority of these functionalities with real historical cases, in which both tools (if operational and accurate) would facilitate the processes of hazard source location, estimation of safe zones, and, consequently, evacuations of civilians.

Having advanced data collection, processing, and computational tools is crucial for the operational mode of the system. However, while doing the research and working out the EU-SENSE concept, both ENCIRCLE and IFARFI studies indicated the need for training and simulation tools allowing for running complex training sessions. At the time, lack of proper training and simulation software was listed among high priority capability gaps of first responders. As a result, the implementation of training mode was incorporated into the EU-SENSE system concept.

At the requirement elicitation phase, the stakeholders and end-users listed many requirements that the training mode should meet. Among other things, the end-user expected a scenario builder embedded in the tool to have the ability to create additional scenarios and change the variables related to the chemical hazard, weather, and node position. Moreover, it was requested to implement the option to simulate/analyse historical cases. Additionally, the training mode should have the functionality to simulate sensor nodes, which has been solved via the implementation of a synthetic sensor node.

Having established the set of prioritized technical requirements, it was possible to focus on system design [18]. While designing this complex system composed of multiple software components, the consortium followed the system-of-systems approach, meaning that the EU-SENSE is going to be composed of multiple software components that could be operated independently. Each component was designed as a black box to ensure proper handling of the intellectual property rights of partners to their particular components. At a very high-level, the EU-SENSE system has been divided into several layers, namely: situational awareness layer, network layer, and computational layer. The situational awareness layer was designed as a layer responsible for the management of the system and providing users with complementary information and visualisations generated by the system. This layer also consists of the training mode, which was ultimately designed as an embedded module of the SA tool. The network layer comprises all elements responsible for data collection such as the network of sensors controller, sensor node, and synthetic sensor node. The last but not least, EU-SENSE has a computational layer, which combines all post-processing tools including data fusion, environmental noise learning tool, source location estimation tool, and hazard prediction tool. The key blocks are shown in Figure 5.

The system architecture has been implemented as a 4+1 architectural view model. It was agreed that the architecture will focus on selected views such as development, logical, process, and physical views. The development view describes the system architecture from the perspective of a developer. The other view, logical, presents the system functionalities as a whole and elaborates on individual components. The process view illustrates the system behaviour while the physical view focuses on deployment schemas. It is worth mentioning that the EU-SENSE system architecture was developed iteratively, which helped to

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[6] Network asset – here the phrase is used to refer to sensor nodes in various configurations (stationary and person-worn), and a weather station deployed in the area of interest.

incorporate changes, which either stemmed from the end-user feedback or technological change necessary for system improvement.

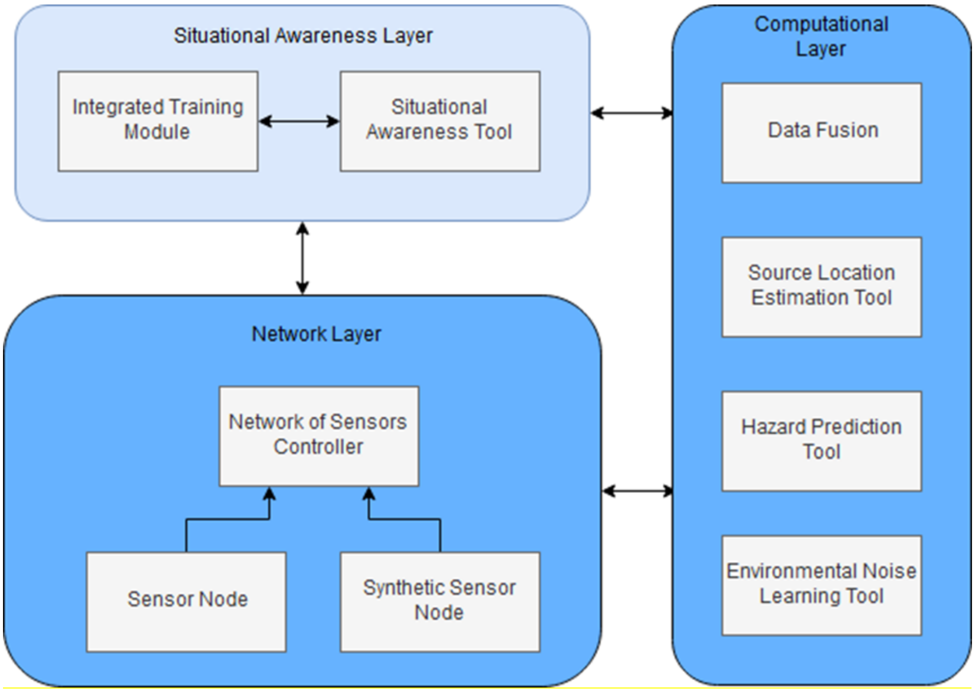

Figure 5 EU-SENSE high-level view

As mentioned above, the EU-SENSE network has been implemented as a system integrating several system layers. For the sake of the deployment in changing and often difficult environmental conditions, it was necessary to come up with a reliable communication structure. Starting from the lowest data acquisition layer – Sensor node – the device based on STM microcontroller integrates 4 different chemical detection instruments. The node design allows end users to connect detectors via cable (the node has USB, and RS232 interfaces to accommodate cable connection of all sensors) or wireless (Bluetooth module allowing for the collection of sensor data). The cable connection is more reliable (by design) and has been recommended for the stationary node setup. The wireless connection is destined mostly for the mobile (or person-worn) setup of the node.

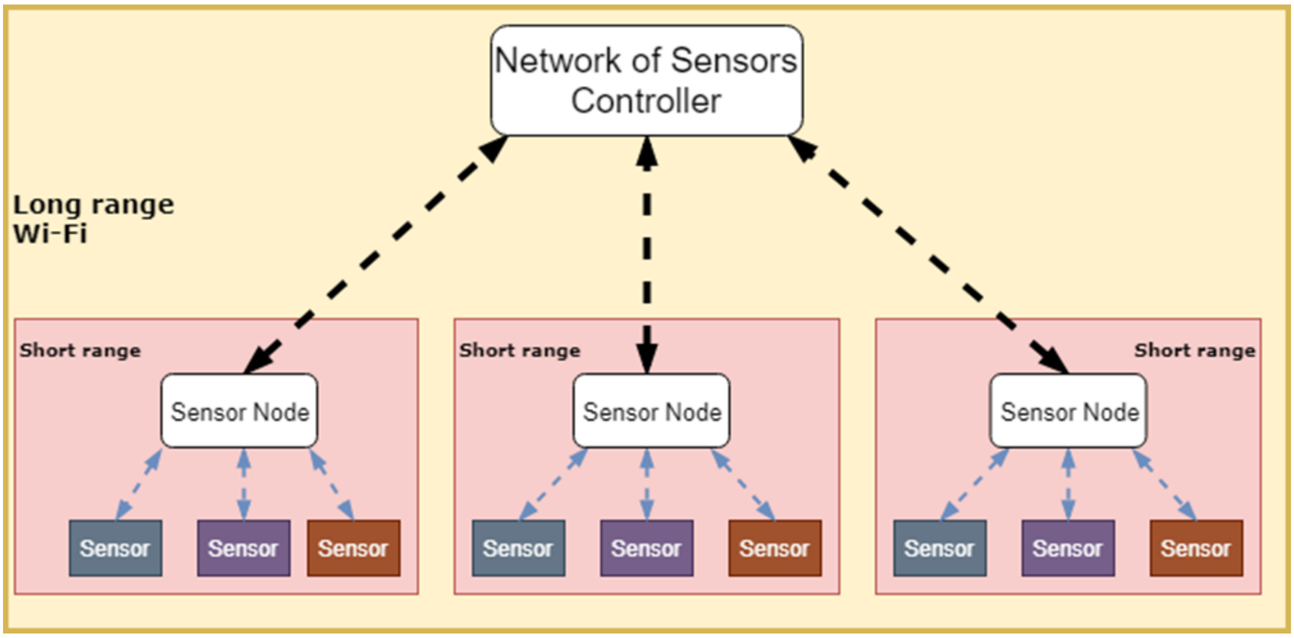

Figure 6 EU-SENSE internal connection scheme

As shown in Figure 6, the data from the senor node are further transmitted to the network of sensors controllers. The data are transmitted via Wi-Fi devices and protocols. As can be noted in the figure above, each sensor node and its integrated sensor set constitutes a smaller sub-network. When combined and connected to the network of sensors controller, they constitute a larger, long-distance network. The advantages coming out of such configuration include:

- A shorter distance between data transmitting devices allows for the use of low-power transmitters
- Network of sensors controller and individual sensors do not require line of sight deployment
- Easier network management when divided into sub-networks.

Having discussed the core functionalities, system layout, and communication aspect of the network, it was also necessary to develop a concept for the training mode of the EU-SENSE system. The key requirements have been already mentioned, however, the nature of this mode is slightly different as it should be a simulation-enabling tool for first responders. This training mode concept was reported under the *D3.5 Training and Simulation Mode Concept* [19].

The Training Mode concept assumes equipping end-users with a tool that would enable conducting training sessions in previously prepared synthetic environmental data. Thanks to this tool, the end-user would gain the necessary knowledge on the operation of the EU-SENSE sensor nodes and their configuration. The training mode concept also described the need to ensure the same user experience while using the operational mode of Situational Awareness Tool and training mode. Moreover, the training mode was supposed to offer the same functionalities as SA Tool. According to end-users involved in the project, the training conduct is encapsulated by three aspects, i.e. familiarise, conduct, and summarise. The explanation is shown in Figure 7 below:

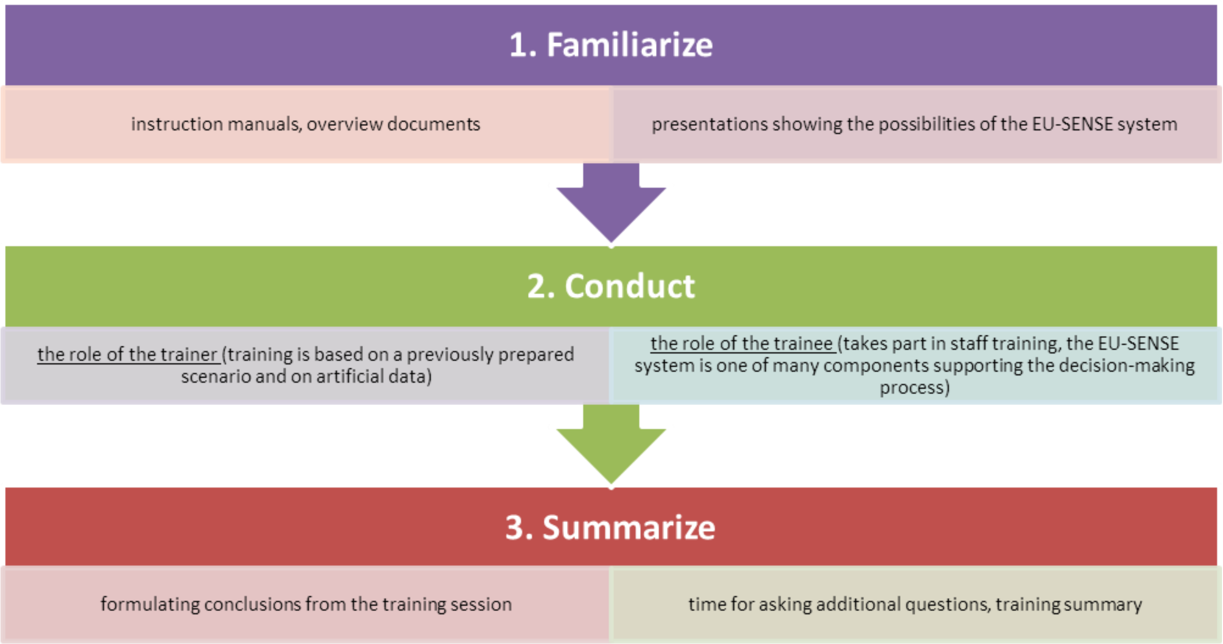

Figure 7 Assumptions of the training concept

For the sake of training mode concept development, it was important to define the so-called User Input. By user input, the concept assumed the ability of the end-user to manually define the source strength of the chemical agent, its location, the starting time of the action/release, as well as weather conditions. The calculations related to estimated source location and hazard prediction would be processed by the same dispersion engine as in the case of operational SA Tool mode. An essential step in developing an operational training mode was the necessity to consider the sensor node deployment for simulation purposes. The concept, defined at the early stage, indicated the need for synthetic node implementation, which could be distributed by the end-user over the area of interest map.

This concept also envisioned the implementation of functionalities enabling review of past historical cases (later the mode was called historical sub-mode), which could be stored in a local database. As a starting point, the concept assumed building two EU-SENSE scenarios into the historical database, which would illustrate the possibilities of the tool. The implementation and development process of the training mode was realised under WP6. Consequently, the outcome of the development process is discussed in section 3.7.

3.5 WP4 EU-SENSE Sensor Node Development

The objective of work package 4 (WP4) was the development of an EU-SENSE sensor node. This sensor node should host all chemical sensors and serve as a data hub. WP4 focuses on the hardware and software development of the EU-SENSE sensor node the core element for the network of stationary and transportable sensors, as well as on-sensor models which will be used in the simulation module to provide mock data. The WP also envisaged the adaptation of relevant sensor devices to fit EU-SENSE purpose, node evaluation, and revision activities.

The main objectives of WP4 are:

- To develop an EU-SENSE sensor node
- To adapt existing state-of-the-art sensors to the node
- To evaluate and revise the developed solution

As described in the paragraphs before the main components of the EU-SENSE system comprise a chemical detection system, a situational awareness tool, and a training and simulation module. The chemical detection system will consist of a network of sensors supported with novel data fusion algorithms.

The following results have been achieved:

- Familiarization with the specific sensor technologies (AP4C, GDA-P (2 variants), TNO MO-sensors) for this project as a basis for design and development activities
- Initial analysis of provided sensor data
- Hardware and firmware concept for the EU-SENSE sensor node
- Initial test of the EU-SENSE sensor node in the laboratory and outdoor
- Acquisition of first measurement data
- Revision and consolidation of the EU-SENSE sensor node hardware – at least 3 hardware versions were prepared
- The final version of the standardized transmission protocol
- Development of a tool for online monitoring of measurement data
- Extensive test of the EU-SENSE sensor nodes in a wind channel, acquisition of measurement data
- Final tests and evaluation of the EU-SENSE sensor nodes in the laboratory as well as outdoor

3.5.1 Employed sensor technologies

3.5.1.1 Ion mobility spectrometer (IMS)

As the most important building brick of the EU-SENSE sensors, the consortium has selected the GDA-P from Airsense. The GDA-P is a handheld device with an IMS and one additional sensor based on another technology. Especially the IMS is expected to provide a high potential for identification of a substance.

With ion mobility spectrometers, drift times are measured that ions require to go through a defined drift path. In this type of time-of-flight spectrometers, the drift of the ions forced by the electric field E takes place at atmospheric pressure, so that the drift time is significantly influenced by the number of collisions between the ions and the neutral air molecules. The velocity of the ions v_d can be expressed by the following equation:

$$\vec{v_d} = K \cdot \vec{E}$$

K is the so-called ion mobility of a specific ion. The mobility of the ions is dependent on pressure and temperature. To obtain substance-specific ion mobility constant, the ion mobility, with knowledge of the environmental conditions, is referenced to $P_0 = 101{,}325\ kPa$ and $T_0 = 273{,}15\ K$:

$$K_0 = K \cdot \left(\frac{P_1}{P_0} \cdot \frac{T_0}{T_1}\right)$$

The ion mobility constant K_0 is the basis for the identification of target compounds. Figure 8 shows the main compounds of a time-of-flight ion mobility spectrometer.

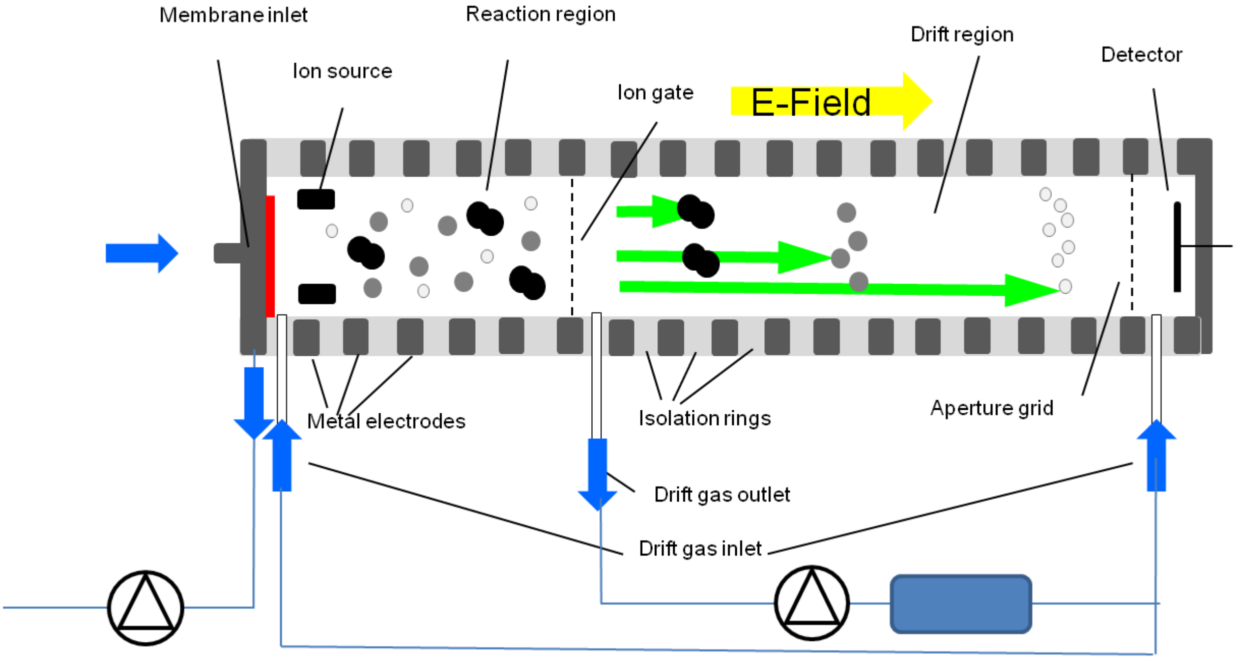

Figure 8 Elements and setup of an IMS

Two different variants of the GDA-P are used in EU-SENSE:

- **Variant 1**: **IMS (H_20-chemistry)** with an additional electro-chemical cell (EC)
- **Variant 2**: **IMS Ammonia (NH_3)-doped** with an additional Photoionization detector (PID)

Doping of an IMS is a common practice to mask interfering substances (with low proton-affinity) and thereby improve detection quality for the targeted substances. Ammonia as a dopant is for example useful when targeting CWAs as target substances for identification. The Ammonia masks (“hides”) many TICs and thereby reduced false identifications due to interferences. Each EU-SENSE sensor node will consist of one GDA-P Version 1 and one GDA-P Version 2.

The communication interface to the GDA is a serial interface, which also is accessible via Bluetooth. The data is received in a streaming fashion with a sampling rate of approx. 1 Hz (1 measurement vector per second).

The IMS systems acquire both positive and negative ions. Accordingly positive and negative IMS spectra are available for data processing. The GDA provides individual access to the additional sensors (PID or EC) and some additional internal environment sensors (temperature, pressure, etc.). There is also some additional information derived from the raw data or provided as meta-information ("channels" derived from the spectra, calibration information, control information).

The GDA-P enables the identification of detected compounds. The identification is library-based. Targets for identification have been specified and will be implemented into an EU-SENSE library.

The following table contains the essential logical data that are available from the GDA-P for processing:

What	Rationale
Positive and negative IMS spectrums as a function of world time (UTC).	Identification of specific substances. Detailed anomaly detection.
Dilution, Temperature, Pressure, Positive and Negative Voltage as a function of world time (UTC).	Technical values may be the cause of anomalies. Technical anomalies should not trigger alarms. Values can be used to monitor sensor health.
Calibration information	For the processing of data on a pre-calibrated basis.

Additional data will be provided by the GDA-P:

- Metadata on the sensor (identification, sensor type, etc.)
- Status information
- Identification and concentration estimate from the sensor if applicable (for validation & comparison as well as processing in EU-SENSE)
- Alarm values from the sensor if applicable (for validation & comparison)

3.5.1.2 Photoionization detector (PID)

For the measurement principle of a photoionization detector, the molecules to be measured are ionized using a UV source. The resulting charge carriers are attracted within an electric field of an anode, respectively cathode. A self-adjusting current corresponds to the present concentration of molecules.

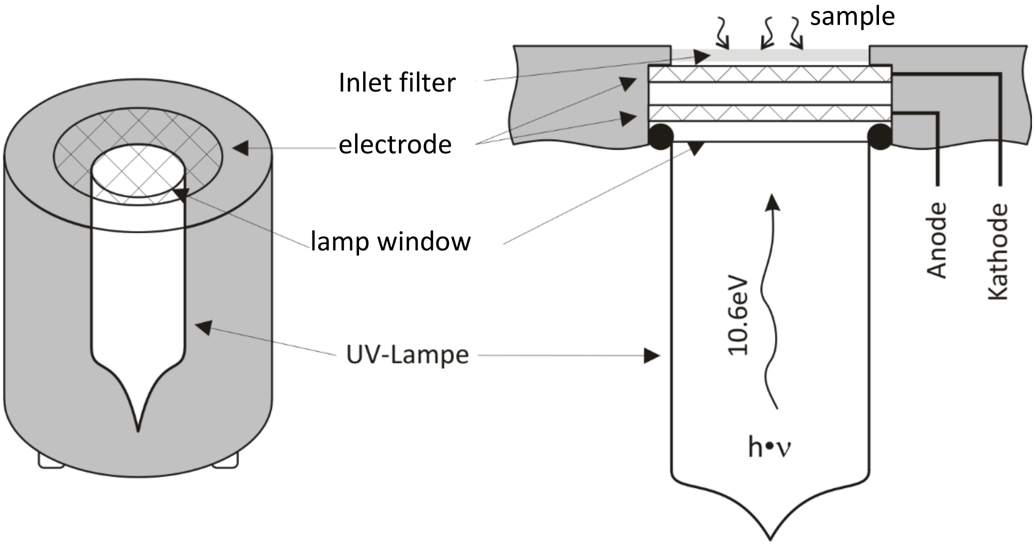

Figure 9 Elements and setup of a PID

Figure 9 illustrates the functional design of a photoionization detector. The left part of the picture shows the typical housing shape of a commercially available detector with its most essential elements. A centrally mounted UV gas discharge lamp emits photons into the inlet area with the electrode stack. The detailed sketch on the right shows a cross-section through the functional area of the detector. The ionization area is accessible to the sample through a particle filter. If molecules (AB) reach this range and their ionizability is below the UV potential of the UV lamp, they are first excited by the emitted photons (hv). The excited state of the molecule leads to the release of electrons, resulting in two charge carriers.

$$AB + h\nu \longrightarrow AB^*$$
$$AB^* \longrightarrow AB^+ + e^-$$

The resulting electrons and cat ions are separated by the applied electric field. A current flow is established via the external wiring between the electrodes.

The detection of gases is strongly dependent on the ionization potential of the gas molecules. Typically, UV lamps are used with radiation energies of 8.4 eV to 11.8 eV. How strongly a photoionization detector reacts to a substance is expressed by the response factor of the respective substance. This depends largely on the required ionization energy in relation to the ionization potential of the lamp. Lamps with 10.6 eV ionization energy offer a long service life and are suitable for ionizing volatile organic compounds (VOCs) and used for the EU-SENSE sensor node.

The following table contains the essential logical data that are available from the PID for processing:

What	Rationale
Sum signal of volatile organic compounds	Detection of compounds with an IE below 10.6eV
Concentration information	Linear concentration information if the response factor is known

3.5.1.3 Electrochemical cell detector (EC)

Electrochemical cell detectors are mainly found for the detection of inorganic substances. The selectivity of the cells is largely determined by the nature and reactivity of the electrode material and the diffusion behaviour of a membrane.

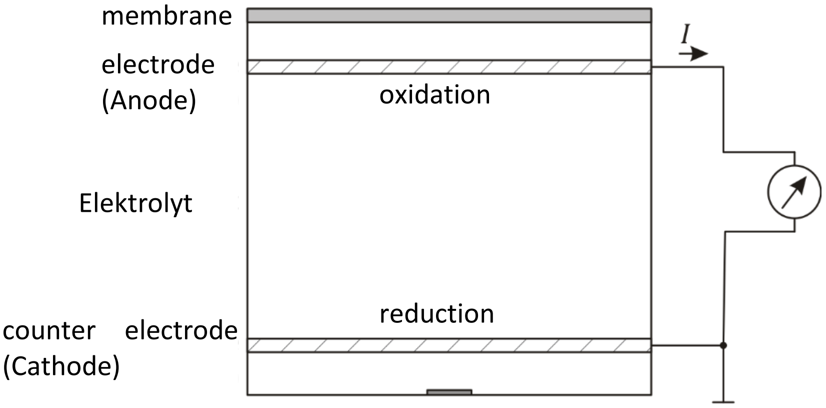

Figure 10 Elements and setup of an EC

The structure shown in Figure 10 describes the main components of an electrochemical cell for substance detection. Through a membrane, the target substance can penetrate the reaction space. Between the two electrodes, separated by an electrolyte, a redox reaction can take place. The resulting potential difference between anode and cathode generates a current flow through an external circuit. An amperometric determination of the current gives information about the present substance concentration. Based on the following functional principle of a cell with the target gas phosgene, the physical behaviour of electrochemical cells is shown as an example.

The electrodes of a phosgene cell are typically made of silver. At the anode, an oxidation reaction takes place with the measuring gas. In this case, silver chloride, carbon dioxide, hydrogen ions, and free electrons are formed as reaction products from the sample gas, the silver of the measuring electrode, and water from the electrolyte.

$$COCl_2 + 2Ag + H_2O \rightarrow 2AgCl + CO_2 + 2H^+ + 2e^-$$

The carbon dioxide is released through the membrane back to the environment. The resulting hydrogen ions diffuse through the electrolyte to the counter electrode. Together with oxygen and negative charges, water molecules are formed.

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$$

The oxygen required for this reaction comes from the ambient air. The negative charges released during the oxidation and required for the reduction cause a charge shift between the two electrodes. A potential equilibration between the electrodes takes place through external circuitry. The current is measured and used as a measure of the present phosgene concentration.

What	Rationale
Reasonable selective signal for inorganic compounds, low cross-sensitivity	Detection of specific target compounds
Concentration information	Linear concentration information if calibration data are available

3.5.1.4 Flame photometric detector (FPD)

The Flame-Photometric Detector (FPD) is provided by PROENGIN in the version AP4C. The AP4C granted access to 5 “concentration” channels calculated internally by the AP4C for:

- CH (Hydrocarbon)
- As (Arsenic)
- CHNO (Cyanide)
- P (Phosphorus)
- S (Sulphur)

In addition to the above-mentioned channels, the AP4C can transmit status information, which can be used to technically monitor the sensor’s health. The AP4C requires hydrogen for operation. For long-term measurements (> 10 hours) a system independent long-term hydrogen supply is available.

Based on the available information, general considerations, the following findings –related to the AP4C– are be important for EU-SENSE:

- The need for hydrogen is problematic for the long-term use of the AP4C. A solution for continuous hydrogen supply has to be found.
- Although no access to the raw emission spectrum is possible, we expect that using the above-mentioned “channels” is also helpful for anomaly detection and orthogonal fusion.
- Information from the AP4C is considered to be helpful when it comes to the identification (or pre-classification) of target substances. Due to its different response characteristics (compared to the IMS and other sensors), it has the potential to reduce false positives through interfering substances (orthogonal fusion).

The following table contains the essential logical data, which should be gathered from the AP4C for processing:

What	Rationale
Channel information as mentioned above	Essential data for anomaly detection and pre-classification/identification within EU-SENSE.
Additional control- and status-information	Technical values may be the cause of anomalies. Technical anomalies should not trigger alarms. Values can be used to monitor sensor health.

As for all of the other sensors within an EU-SENSE network, additional data is needed:

- Metadata on the sensor (identification, sensor type, etc.)
- Status information including results of some health check (calculated within the sensor node or at the level of a network controller)
- Identification and concentration estimates from the sensor if applicable (for validation & comparison)
- Alarm values from the sensor if applicable (for validation & comparison)

3.5.1.5 Metal oxide sensors (MOS)

TNO provides a small sensor array of 16 Metal-Oxide detectors, combined into one device, to EU-SENSE (manufacturer SRD). The 16 individual sensors respond in terms of changes of electrical resistance and react in different ways to the same substance.

There are 3 instances of the sensor available for EU-SENSE.

The SRD sensors array also provides additional information on environmental and internal conditions like temperature, relative humidity, etc. Additionally, the sensor itself contains some firmware, which performs identification and concentration estimation on the fly and provides the results with the output values.

The data is collected using a serial interface. The measurement rate is approximately 1 Hz.

The MO-based detectors are a potential candidate for the future need of multiple cheap detection devices.

The SRD-sensors are composed of a detector-box and a laptop for reading out the data. The data stream is processed on the chip of the sensor. For adaptation into an EU-SENSE sensor, the sensor module is coupled with a Latte Panda alpha 486 microcomputers. The microcomputer can read out the serial port of the sensor module and transmit the data over a Bluetooth connection. To enable the operation of the sensor as a stand-alone detection device the system is equipped with a battery pack designed for 12-hour operation without additional maintenance. The total system is integrated into a single box.

3.5.1.6 Sensor integration

This section describes the sensor node structure and functionalities.

3.5.1.6.1 GDA-P

The GDA-P device can communicate via RS232 or Bluetooth link. Because two separate GDA-P instruments are used, to minimize Bluetooth interferences between them, both types of connections were used:

- GDA-P PID – Bluetooth,
- GDA-P EC – RS232.

The instrument can be powered by an external AC power adapter or 14 x 1.5V AA-type batteries (using included battery tray). Original RS232 cable needs to be used to establish a wired connection to the node.

Figure 11 GDA-P

3.5.1.6.2 AP4C

The AP4C requires an original PROENGIN USB adapter, which connects to the Fischer 5 type socket located on the top of the device. The sensor node has the USB port dedicated to the AP4C device. The instrument requires either 2 x 1.5V D-type batteries (using included battery tray) or a dedicated AC power supply. AP4C requires hydrogen to operate, which can be delivered to the instrument by replaceable hydrogen containers or external big capacity hydrogen source (using dedicated pipe connector).

Figure 12 AP4C

3.5.1.6.3 SRD

The SRD sensor can be connected to the node with a standard USB type A connector, there is a dedicated port on the sensor node. SRD box is equipped with a high-capacity power bank, but it can also operate while charging (using the original charger).

Figure 13 SRD sensor box

3.5.1.7 Sensor node hardware

The sensor node is the key element to combine all the sensors. i.e. the sensor data. Figure 14 depicts the hardware version of the sensor node.

Figure 14 3rd generation of the EU-SENSE sensor node

3.5.1.8 Sensor node overview

Table 1 below presents the comparison of all sensor node generations and their features.

Table 1 Comparison of EU-SENSE sensor nodes

Parameter	Generation 1	Generation 2	Generation 2.5	Generation 3
PCB dimensions	120mm x 113mm	70mm x 68mm	88mm x 66mm	88mm x 66mm
Casing dimensions	165mm x 125mm x 46mm	78mm x 119mm x 61mm	110mm x 93mm x 59 mm	110mm x 93mm x 59 mm
Data output	SD card only	SD card, Wi-Fi	SD card, Wi-Fi	SD card, Wi-Fi
Configuration	Hardcoded	Stored on SD card	Stored on SD card	Stored on SD card
GDA-P PID interface	Bluetooth	Bluetooth	RS232	Bluetooth/RS232
GDA-P EC interface	RS232	RS232	RS232	Bluetooth/RS232
MO interface	USB	USB	USB	USB
AP4C interface	USB	USB	USB	USB
Wireless interface	None	Wi-Fi 2.4GHz	Wi-Fi 2.4GHz	Wi-Fi 2.4GHz
Microcontroller	STM32F4	STM32F4 + ESP32	STM32F4 + ESP32	STM32F4 + ESP32
Wireless protocol	*not applicable*	TCP	TCP	TCP + MQTT

Figure 15 depicts the functional diagram of the sensor node. Figure 16 shows the actual setup used for measurement tests and outdoor evaluation.

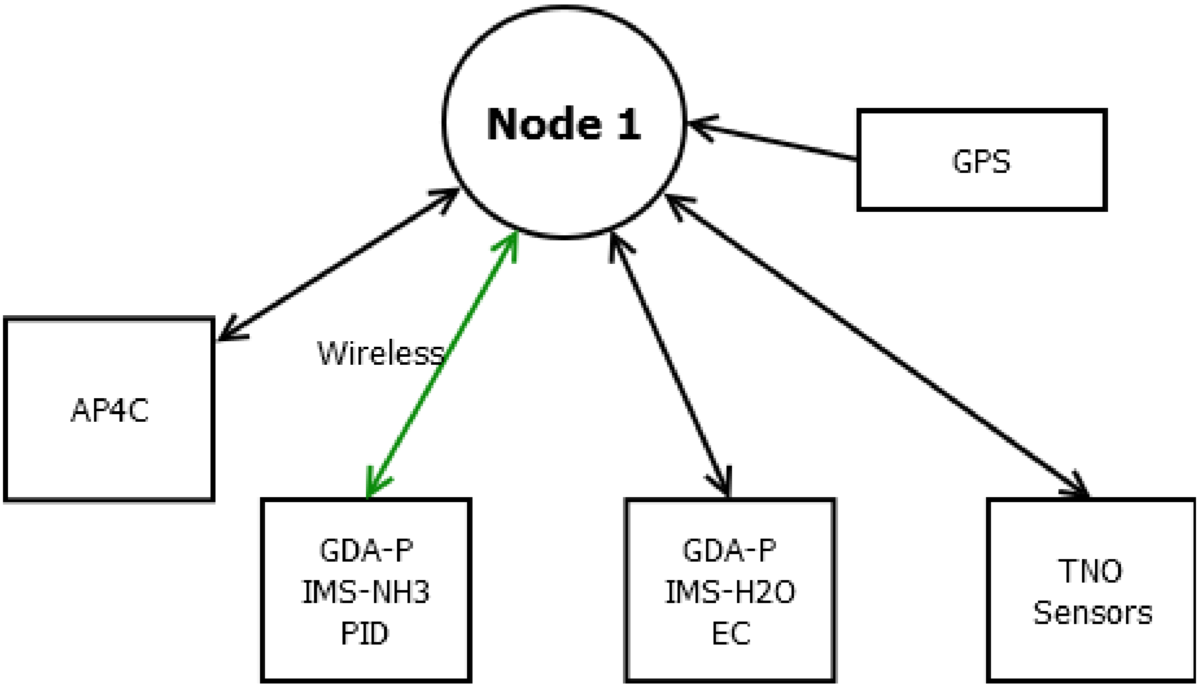

Figure 15 3rd generation of the EU-SENSE sensor node

Figure 16 Complete EU-Sense sensor node with all sensors connected

Work package 4 started in M8 of the project and was scheduled to continue to M28. Due to some delays in the project, the works in work package 4 were extended up to M33. All major development steps are finished, the major functionalities are accomplished.

The functionalities of the EU-SENSE sensor node were tested and evaluated in at least 4 different locations at 4 project partners. Valuable experiences and measurement data could be obtained. The field experiences lead to steady improvements and showed the great need for field tests for obtaining a certain level of stability in operation.

The EU-SENSE consortium has succeeded in successfully integrating sensor equipment of different manufacturers. Integration of different instrumentation and data formats in one sensor node, which can deliver real-time data in a single data frame for integrated processing is a level of integration that is not achieved in the commercial of the shelve systems. The challenge achieved is noteworthy as it opens the way for further system integration in the future.

3.6 WP5 Machine Learning of the Environmental Noise

Fast and robust detection of a chemical incident is paramount to safeguard the life and health of the affected population. The ability to rapidly detect such incidents equates to faster response times, reduced-hazard exposure, and more efficient use of limited resources. Although significant progress has been made in recent years, there are still significant shortcomings in chemical detection technologies.

The EU-SENSE project seeks to address identified high-priority gaps and needs within chemical detection (identified by the ENCIRCLE program) by developing a novel network of sensors through the exploitation of chemical detector technologies, advanced machine learning, and modelling algorithms. The main components of the EU-SENSE system include a chemical detection system. The chemical detection system consists of a network of sensors combined into sensor nodes supported with data fusion algorithms processing the sensor responses continuously to derive the operationally important information and finally be able to trigger an alarm or provide information on the degree of danger.

The objective of this work package was the development of machine learning algorithms for the environmental noise based on raw sensor data in a network of sensors to improve detection accuracy and minimize false alarm rates. To support this work the plan included several measurement campaigns in different outdoor environments. In addition, measurements under controlled environmental conditions (laboratory, breeze tunnel) were necessary to generate necessary data for algorithm development and validation.

During the project, a network of chemical point sensors was developed. This network consists of sensor nodes, where each node is equipped with different sensor technologies: IMS[7], EC[8], PID[9], FPD[10], and a MO[11] Sensor array (for a technology overview see e.g. [12]).

The idea is to place such a network in an area of interest and

1. to detect a chemical attack or accidental release and
2. to estimate the concentration of the detected substance (thereby determining a degree of danger) and
3. to infer information about the source that released the substance and
4. to predict the hazard resulting from that source.

Possible scenarios for this kind of use could be mass events such as sport events, open-air festivals, etc. While WP6 focussed on the dispersion-related points 3 and 4 of this list, WP5 mainly targeted points 1. and 2.

There are several possible interpretations of the term “detection” in such a context and often there are misunderstandings. To avoid some of these pitfalls, we would like to introduce the following main concepts and ideas:

- When talking about the detection system of EU-SENSE, we mean the complete system functionality provided by the components sensor, sensor node, several data-processing steps, and the Situational Awareness component, which technically raises an alarm.
- We use a “detect-to-warn” semantics during the so-called Preparedness Phase (monitoring the environment for possibly harmful situations). The ultimate goal is to reliably raise an alarm if a potentially harmful situation arises. At the same time, we want to avoid any alarm, in situations that are not considered harmful.
- Technically this needs a definition of “harmful”: We assume a situation harmful (requirement to raise an alarm) if a concentration of a toxic substance exceeds AEGL-2 (10 min). Still, we would like to be aware of situations where the concentration is in the range between AEGL-1 (10 min) and AEGL-2 (10 min) in order to have the option to warn/inform the general public.
- Technically, we can only consider substances in a defined target set of substances (the “library”). If a substance is potentially harmful, it should be in the library. In other words, substances not in the library are (technically) -by definition- not harmful.
- Since a perfect detection system does not exist, the number of false positives (alarm when not necessary) and false negatives (no alarm when required) cannot be optimized at the same time. There is an inherent trade-off between those two, i.e. you can only optimize one of them while degrading the other. Therefore, these two factors should not be discussed or judged isolated from each other.
- During the so-called Response Phase, we assume the threat substance to be already known. In this phase, the main objective of the detection system is to monitor the hazard level to support the work of operational units as well as to decide when an alarm can be finally lifted.

At the beginning of the project, some basic considerations were necessary. Based on technical information on the specific sensors, their technology, and some initial measurements, we developed concepts for the necessary data processing steps. Preliminary analysis of the -at that time- available sensor data was

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[7] IMS – Ion Mobility Spectrometer

[8] EC – Electro-chemical Cell

[9] PID – Photo Ionization Detector

[10] FPD – Flame Photometric Detector

[11] MOS – Metal Oxide Sensor

performed and several algorithmic options were explored. The conclusion from these activities, ideas developed in the former project CENSIT [13], and discussion within the consortium finally led to the following steps of data-processing for the detection system:

- Anomaly (or Change) Detection: As a first sensitive step to detect signal changes in a noisy background.
- Classification: Pre-grouping of the situation as seen through the sensors by assigning a rough substance class.
- Identification: Determine the substance(s).
- Concentration Estimation: Estimate the concentration(s) to assess the hazard level.

While during Preparedness Phase all these steps are necessary to execute the detection function of EU-SENSE, in Response Phase essentially only the Concentration Estimation step is necessary.

While initially, only Anomaly Detection was targeted by the project, nevertheless the downstream steps of Classification, Identification, and Concentration Estimation are necessary to build a complete detection system. Work on the latter steps got more and more important in the second half of the project.

A more detailed description of all steps will follow later in this section.

In addition, to the conceptual development and initial exploration, the first project phase also resulted in

- Analysis of lossy compression methods for spectral sensor data (Wavelet Compression). We consider this approach useful with moderate compression ratios at least for IMS spectra. However, it was decided to not implement this approach for this particular system.
- Statistical considerations on validation of the detection system. Many dedicated experiments would theoretically be necessary to statistically significant prove low false positive/negative rates.
- A detailed list of requirements for the necessary measurements.

The planned measurement campaigns started with some delay at end of 2019 (Norway FFI). However, the process of setting up complex sensing equipment and experiments was error-prone and time-consuming. It was not until mid-December when the first useful measurement results were available. The following table shows the schedule of the measurements.

Table 2: Measurement Campaign Periods

Date	Institution	Where
2019 Dec	FFI	Outdoor *ramp-up*
2020 Jan	FFI	Outdoor
2020 Feb	FFI	Outdoor
2020 Mar	FFI	Laboratory
Corona Interruption		
2020 Jun	FOI	Outdoor
2020 Aug	SGSP	Outdoor
2020 Nov	TNO	Outdoor

Date	Institution	Where
2020 Dec	TNO	Outdoor & Laboratory
2021 May	FFI	Outdoor

Laboratory measurements at FFI were planned and started in spring 2020 but had to be ceased due to the COVID-19 pandemic and were left uncompleted. During summer 2020, FOI and SGSP conducted outdoor measurements. In November and December TNO conducted measurements, outdoor and in the laboratory as well. Further, they had the extremely helpful capability to perform measurements in a breeze tunnel, which allows exposure of several sensor nodes to defined concentrations within an ambient atmosphere.

Recently in May 2021, FFI again conducted outdoor measurements in Norway. The results served as test and validation data.

The measurements at a sampling rate of approx. 1 Hz produces a lot of data. The essential part of the responses (w/o the many support values like flags, temperatures, pressures, etc.) are:

- MO sensor: 16 channels
- FPD: 5 channels
- IMS: approx. 900 channels
- PID, EC: 1 channel

These form time series of approx. 2000 values, which are continuously processed by the functions of the system and also need to be stored and visualized. Also, all technical partners needed access to some or all of the data.

To support the efficient processing on the one hand and storage/visualization, on the other hand, we decided to use a dedicated time-series database (Timescaldb[12]) in conjunction with an open-source visualization tool Grafana[13]. Internet access was set up for the consortium to provide access to the data as fast and simple as possible. Usage of the same technical basis for the implementation of the processing software and our own project-internal visualization did avoid unnecessary overhead.

The development activities were accompanied by the development of statistical sensor models based on the theoretical ideas we already had in the former CENSIT project. This was mainly planned as a support activity to compensate for missing data but with the potential to use such a model e.g. for training purposes.

Unfortunately, for a long period, the available data for this development was limited, in particular to background measurements without a signal. Therefore, the focus of the sensor model development was on these background signals. Three flavours of statistical models were used: For sensors like PID and FPD influenced by main factors autocorrelation and noise, for MO-sensor arrays with additional dedicated arrival processes of short fluctuations and inter-channel correlation, and finally for the spectral IMS sensor, where peak positions play a major role. In particular, the usage of the IMS model is complex, since in the case of signals a script is needed to describe the signal over time.

Also as more outdoor background measurements got available it got more and more clear that at least in those environments, we performed the experiments in, a background signal on a larger timescale was not such a big problem for all sensors. Mainly the MO sensor arrays suffer from large (but slow) response

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[12] https://www.timescale.com/

[13] https://grafana.com/

fluctuations. Instead, other sensitive sensors can show shorter (harmless, background) signals in “dirty” environments like the one that was finally identified for the measurements in April/May 2021.

The following subparagraphs will describe the developed detection-related sub-functions in more detail. Figure 17 sketches the responsibilities of system components concerning detection for a better overview.

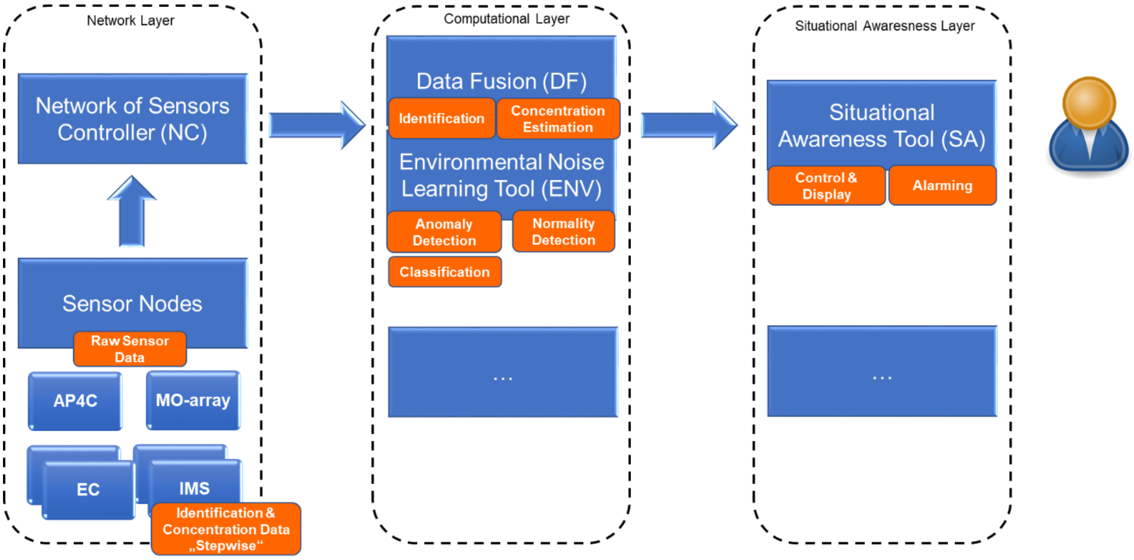


Figure 17: Conceptual System Architecture with detection-related subfunctions (orange)

3.6.1 Anomaly Detection

Anomaly detection is based on raw sensor data collected from the individual sensors. These sensors are combined into “sensor nodes” and, at a higher level, a network of sensor nodes. Therefore, anomaly detection can take place on sensor level, node level, and/or the network level. We decided to use a straightforward statistical, distance-based approach that compares incoming response values against (multi-variate) probability distributions learned continuously from previously seen data (online learning) in different schemes.

The results of anomaly detection eventually are new (one-dimensional) time series (on sensor level, node level, etc.) of anomaly scores. The change detection based on these anomaly scores is sensitive, i.e. small signals result in rather large scores. This is due to the multivariate nature of the many response channels in some sensors or the whole node. If a signal is caused by an incident (or whatever) then it is common that multiple sensor channels will respond to this signal. This can reinforce the distance measure, i.e. the anomaly score.

We executed the Anomaly Detection process on some of our recorded experiments to show that the anomaly detection robustly detects a real incident and that the anomaly detection is sensitive. However, the latter implies that False Positives (at this level) are unavoidable:

- It detects small concentrations
- It detects signals of harmless substances
- It detects artifacts

In this context, it is interesting to reflect for a moment what a false alarm (at the system level) actually is. Is it a false alarm when there is a (low) concentration of a harmless substance in the air containing e.g. phosphorus (e.g. fertiliser) and the FPD (P channel) responds to that? Obviously, the sensor does exactly what it is supposed to do and from this perspective, this is not a false alarm. However, it is a false alarm for emergency personnel since the substance is harmless in a low concentration. Therefore, it is necessary to verify, whether an anomaly is a real incident. That is why other techniques like Classification, Identification, and Concentration Estimation are important. The following discussion contains examples for the above-mentioned anomaly cases.

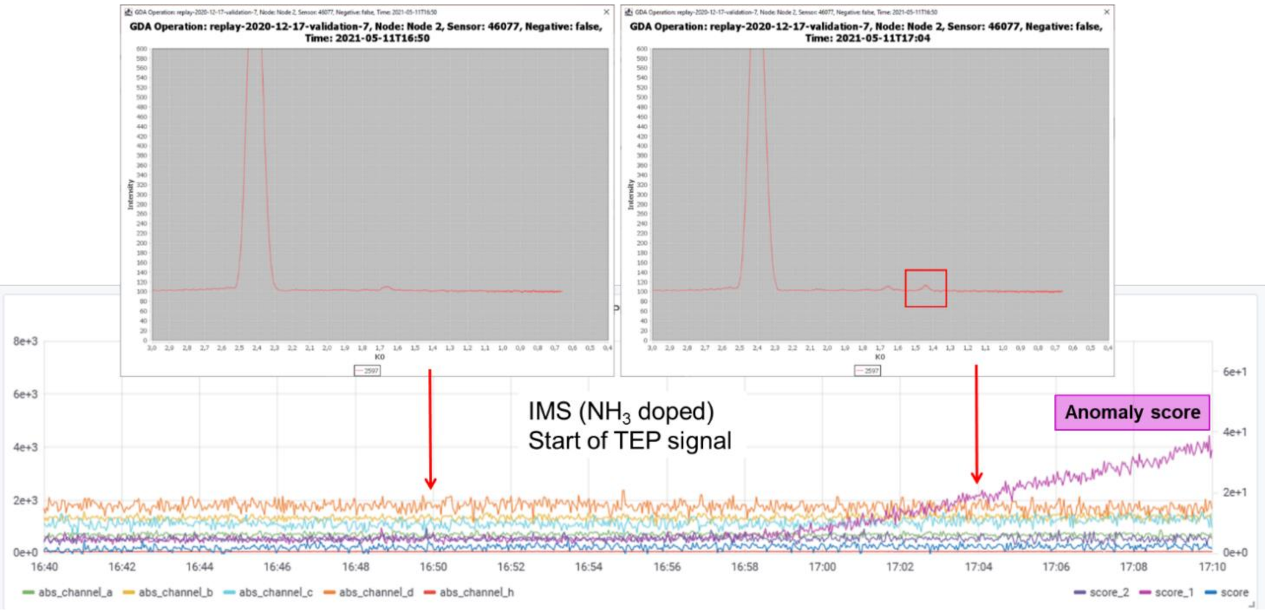


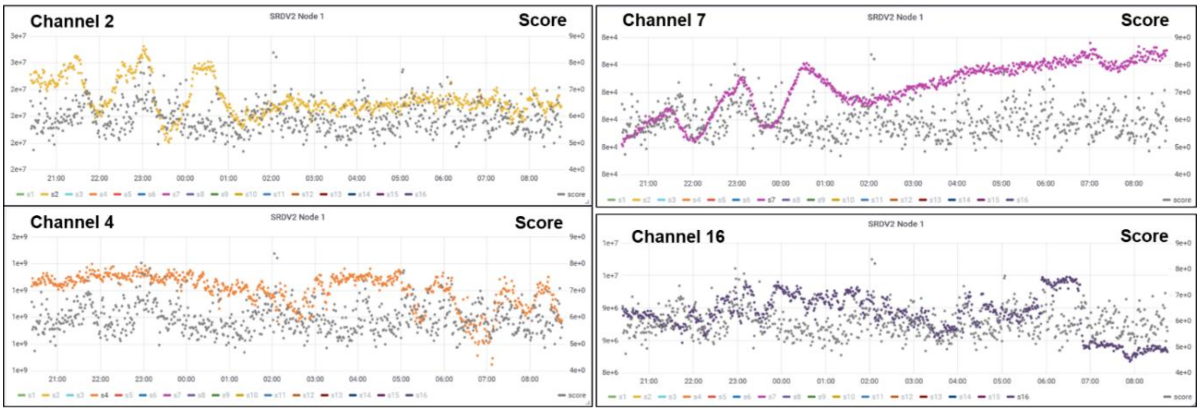
Figure 18: Example Anomaly Score on small-signal

Figure 18 shows an example of the Anomaly Score calculated on the positive spectrum of an IMS (below, magenta, score_1) before (corresponding to the left spectrum) and after (corresponding to the right spectrum) a signal is visible. The red arrows mark the time, i.e. the signal is already detectable earlier since the score is already far beyond the usual noise level of the score series.

In contrast, Figure 19 shows an example of 12 hours without a relevant signal. The data stems from an outdoor measurement recorded in the Netherlands and shows 4 out of the 16 raw channels of one of the MO sensors (colored, left axis corresponds to channel value). Additionally, in each of the plots, the calculated Anomaly Score (grey, right axis) is visualized. We can see several kinds of raw signal changes. We have fluctuations at different times (Channel 2, 3), drift (Channel 7), and also a rather abrupt change (Channel 16). Nevertheless, the Anomaly Score more or less “flattens” these changes out since these changes are considered in the normal range (according to the used configuration). In this case, no signal anomaly/change would be detected.

Another important kind of “background” signal is common with the use of IMS sensors: If these instruments are not cleaned carefully before and after usage, they can be contaminated (from storage or usage), i.e. do not show a perfectly clean spectrum. However, this distorted spectrum is learned as a “normal” situation and even it then changes slowly during runtime, this will not trigger a detected change.

Shown period: Approx. 12 h – **No Signal**



MO sensors – Background Measurement NL

➢ **Usual fluctuations are ignored**

Figure 19: MO sensor background signal

Figure 20 then is another example of a sudden, strong change of an MO sensor signal (Channel 16, purple, left axis) and the corresponding Anomaly Score (light green, right axis). In this case, no signal was present and due to the Anomaly Score, a change would be detected. Actually, channel 16 of one of the MO sensors did show comparable behaviour on a regular basis. We assume this to be an artifact of these sensors (which are still in an experimental stage).

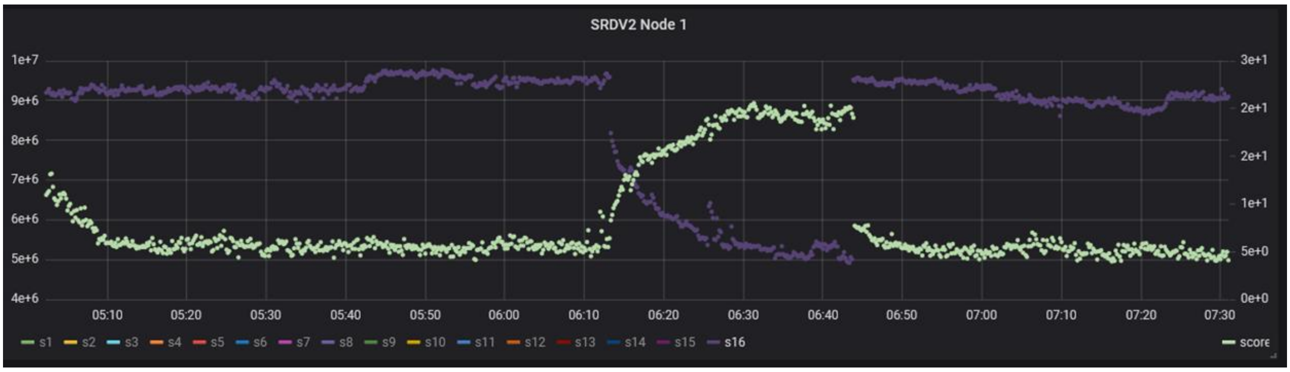


Figure 20: Sudden change on MO sensor

Other unintended signal changes can of course occur from harmless substances in the air. Figure 21 shows such an example from background measurements on a half-closed tunnel environment with much traffic, recorded in April 2021. The left plot shows a positive IMS spectrum before the signal, the right plot shows the same spectrum when the signal change was detected. The downstream processing steps must sort these cases out to avoid false alarms at the system level.

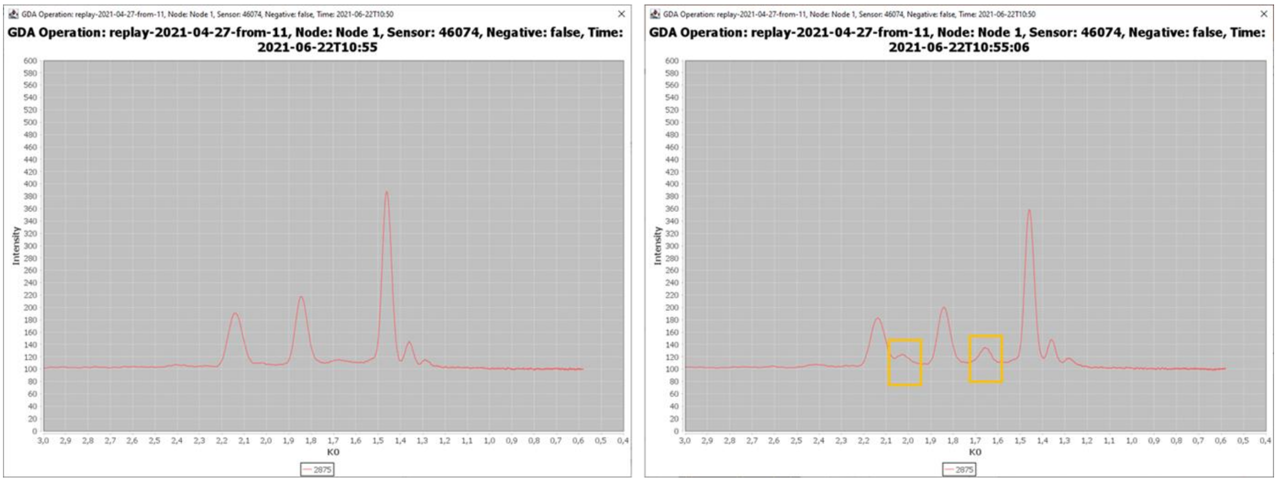


Figure 21: Harmless signal

3.6.2 Classification/Identification

The second step in the detection of a real incident is identification. Only when a signal is identified as harmful (substance, concentration) one can speak of a real incident and raise an alarm.

Identification is performed for each node because it can be assumed that all sensors at a specific node are exposed to the same agent concentration[14]. This is not necessarily the case for two distant nodes. Ideally, Identification should also make use of all the detection technologies available at that node.

We pursued two main approaches: The “fusion approach” and the “stepwise approach”.

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[14] Ideally, the sensors would be connected with a common inlet. This was not the case in our work

Fusion approach

This approach is the prototypical development through a fusion of all available sensor information at a node with Bayesian inference only with the knowledge gained from the experiments in the EU-SENSE project itself (i.e. no knowledge is incorporated from the sensor manufacturer).

Stepwise approach

This approach relies solely on the existing sensor technology available at the inferring node implicitly including the necessary knowledge of the manufacturer (in form of substance libraries). It consists of the two steps:

- Classification, i.e. assigning the observation to a substance group (e.g. phosphorus-containing agents), thereby narrowing down the whole range of possible substances.
- Simultaneous Identification & Concentration Estimation through IMS technology based on existing substance libraries.

While both approaches have to be considered prototypical, the stepwise approach relies on existing technology, i.e. reuses prior knowledge available to the sensor manufacturer. In contrast, the fusion approach had to be built from scratch with only the data available from our measurements. The number of substances measured in trials and experiments was limited and therefore only some target substances (namely NH_3, TEP) could be used. However, this is more or less a problem with every newly developed identification system.

3.6.2.1 Fusion approach

This approach makes use of Bayesian Networks which process knowledge contained in the so-called conditional probability distributions and prior distributions. This knowledge was derived from training data collected during the TNO experiments in November and December 2020. This report is not the place to explain these methods in-depth. Instead, we refer to the relevant literature to Bayesian Inference available in abundance; see e.g. [14], [15], [16].

The core of the identification is a Bayesian Network like the one shown in Figure 22. The hypotheses variables are substance and concentration. Both are discrete variables, i.e. they have a finite number of levels.

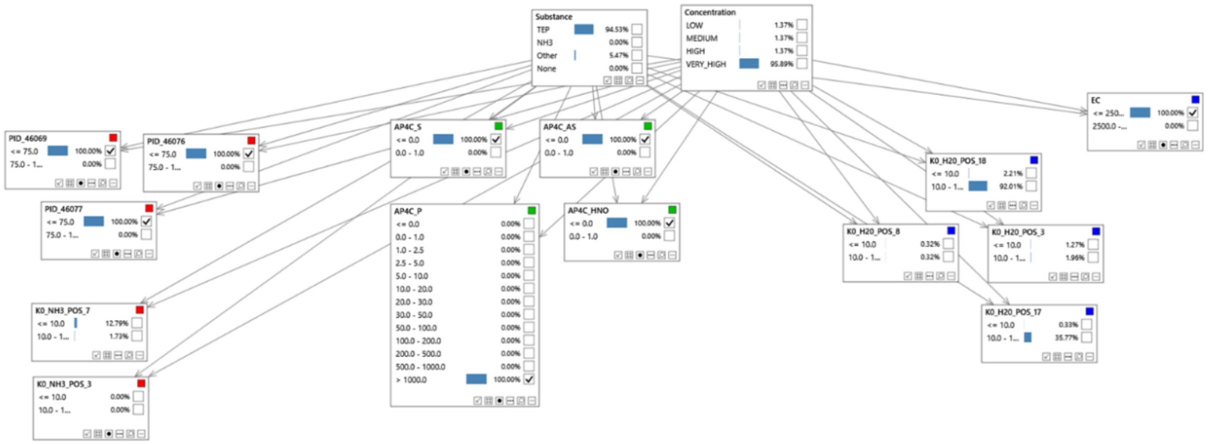


Figure 22: Bayesian network for identification (with feature pre-selection)

The hypothesis variable concentration has four levels, i.e. the concentration values are assigned to four classes corresponding to the AEGL (10 min.) values:

- LOW (< AEGL1),

- MEDIUM (< AEGL2),
- HIGH (< AEGL3),
- VERY_HIGH (> AEGL3).

For the hypothesis variable substance, the following substance classes are used:

- NH3
- TEP
- Other: other substance or somehow inconsistent concerning the implicit knowledge.
- None: Not actually a substance; corresponds to a very low signal

The method aims at estimating these two values (as a probability distribution) from input provided to the so-called observation variables (the leaves of the shown tree/network), which correspond to our sensor responses. Note that not all available sensor response variables are represented in the network. The relevant response values have been identified through a relevance analysis during training time. Of course, this selection is substance-specific. I.e. sensor values that do neither respond to NH_3 nor TEP do not appear here. Despite this down-selection for simplicity reasons, you can easily add all sensor channels here (which we have done for variations of this scheme).

The scope of the classification or identification is limited to four substance classes. As mentioned, no other reliable substance information was available to us within the project. However, the method is easily extensible if new information is available. Even though the algorithms were implemented in software, they have not undergone a final optimization for real-world use and we consider this a proof-of-concept implementation.

Note that even different instances of the same sensor may be too different to model them uniquely. This is the reason why in the Bayesian network in Figure 22 there are three different PID sensors as response variables of the GDA PID. Actually, the Network relates to one node and every node has only one PID. However, the differences in response characteristics of the three PIDs are so large, that they need to be treated as different sensors. When applying the network to a particular node only the response of the PID for that node needs to be specified. Also generally, the input to the response variables can be partial, i.e. it is not necessary to specify all the response values. The Bayesian inference will nevertheless work properly.

The formulation of the identification problem with this Bayesian network implies the assumption that the node is exposed to a concentration of a single substance. This leads to inconsistencies when the presented concentration is a mixture of two or more agents. Although the classifier can identify NH_3 or TEP correctly, it will come out with the classification OTHER when the node is exposed to a mixture of both. Actually, this is technically correct. Nevertheless, this is somehow unsatisfactory and we propose to reformulate the problem.

3.6.2.2 Stepwise approach

The “stepwise-approach” is an engineering approach relying on the output of existing sensor technology at the inferring node including the prior knowledge integrated by the manufacturers. The basic idea is to utilize orthogonal sensor fusion in order to reduce the size of the IMS identification libraries. Narrowing down the set of possible substance candidates avoids false positives (substance identified due to a harmless disturbance signal) as well as confusion of substance candidates (overlaps of drift time windows). The substance libraries contain prior knowledge of the IMS manufacturer. Therefore, no additional experiments/tests are necessary in order to gather response relationship information, etc.

As the first step after an anomaly detection, the classification step derives information about substance groups (Classification).

This information then is used to reduce the substance library and to obtain directly the GDA (IMS) results containing simultaneously identification and concentration estimates. Figure 23 sketches this process. Due to the Classification of classes I and IV, a sub-selection of the identification occurs (also results from Default, which is always included). The * indicates that the concentration estimates might be fused from the results of both available IMS sensors.

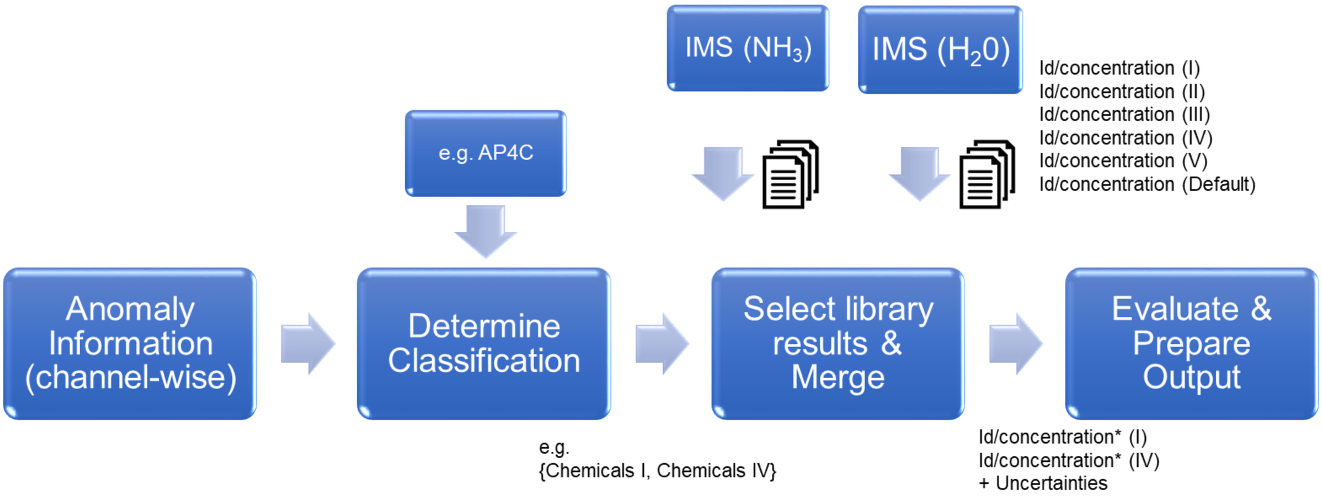


Figure 23: Processing scheme "stepwise"

3.6.3 Concentration Estimation

Concentration estimation is important for dispersion-related fusion (WP6) as well as the performance of the detection system of EU-SENSE in order to determine the hazard level. However, concentration estimation is also difficult due to several reasons including the underlying physical process (turbulent diffusion), the performance of the sensing technologies as well as the effects induced by background signals. In summary, the inherent uncertainties are large. The above-mentioned stepwise approach naturally uses the outputs of single sensors (IMS) without quantifying uncertainties. As an alternative approach to concentration estimation, we implemented a regression scheme again based on Bayesian inference/networks. Since this is a regression task (instead of a classification task as with identification), we now use continuous variables (and probability distributions).

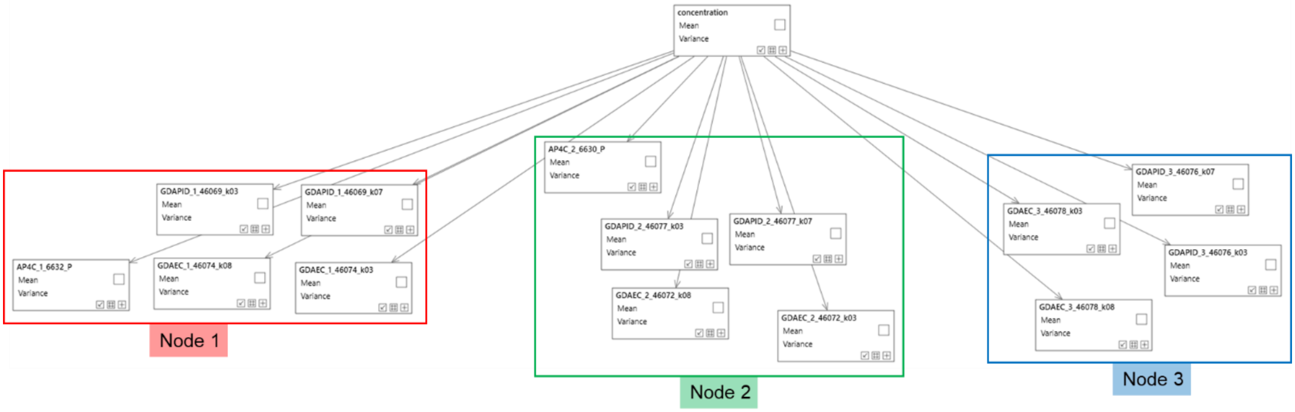


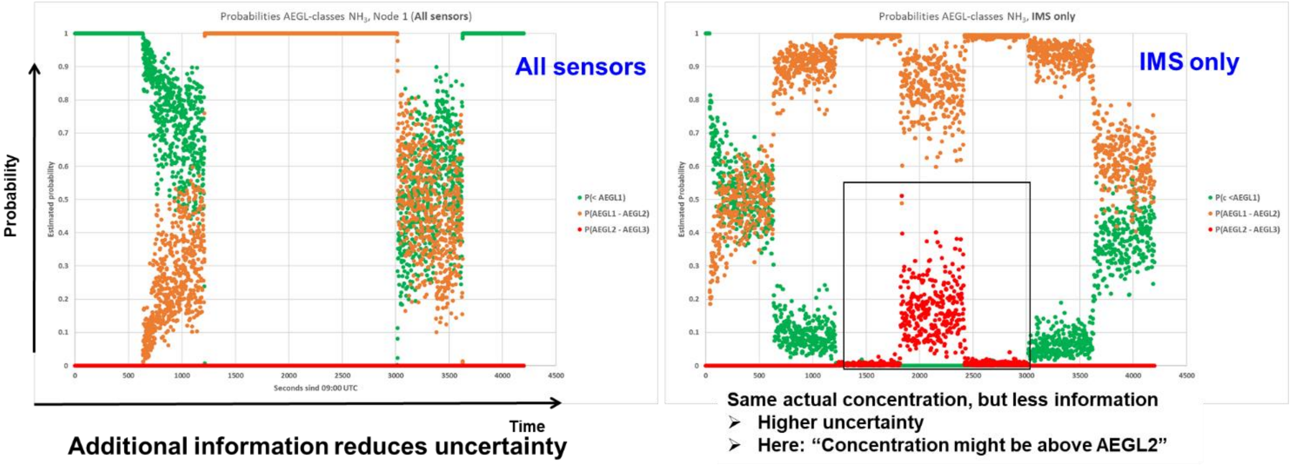
Figure 24: Bayesian Network Concentration Estimation

Figure 24 shows a Bayesian network for the estimation of one of our target substances (TEP) as an example. We assume the substance as given, estimate the concentration (root node, hypothesis variable) and the approach again relies on feature pre-selection. That is why we use only some of the sensor response variables.

The necessary prior knowledge was derived solely from the TNO measurements in December 2020 and converted to the necessary (conditional) probability distributions using an EM (Expectation-Maximization) algorithm. This approach is extensible, i.e. new response variables can be added or updated one after the other. Due to the nature of the method using approximations of parameterized probability distributions, comparatively low amounts of training data were sufficient.

Again, partial input to this algorithm is sufficient. If we only have a PID available, we can use that information to do the estimate, which might however result in larger uncertainties as if we have other sensors (e.g. an FPD) in addition. We are able to use the best available information at a sensor node.

The method comes with another practical benefit: It estimates the concentration uncertainties, thereby allowing to make them explicit and use it to inform personnel.



Additional information reduces uncertainty

Same actual concentration, but less information
- Higher uncertainty
- Here: “Concentration might be above AEGL2”

Figure 25: Example: Estimated Uncertainties by AEGL-class

Figure 25 shows an example of calculated probabilities by concentration class (AEGL (10 min) aligned) using information from PID, FPD, and IMS (All sensors; left) and an IMS only (right) using the same measurements. Green is the probability for a very low concentration (below AEGL-1), Orange represents the range between AEGL-1 and AEGL-2, and Red the range between AEGL-2 and AEGL-3. The corresponding concentration profile (estimated) is shown in Figure 26.

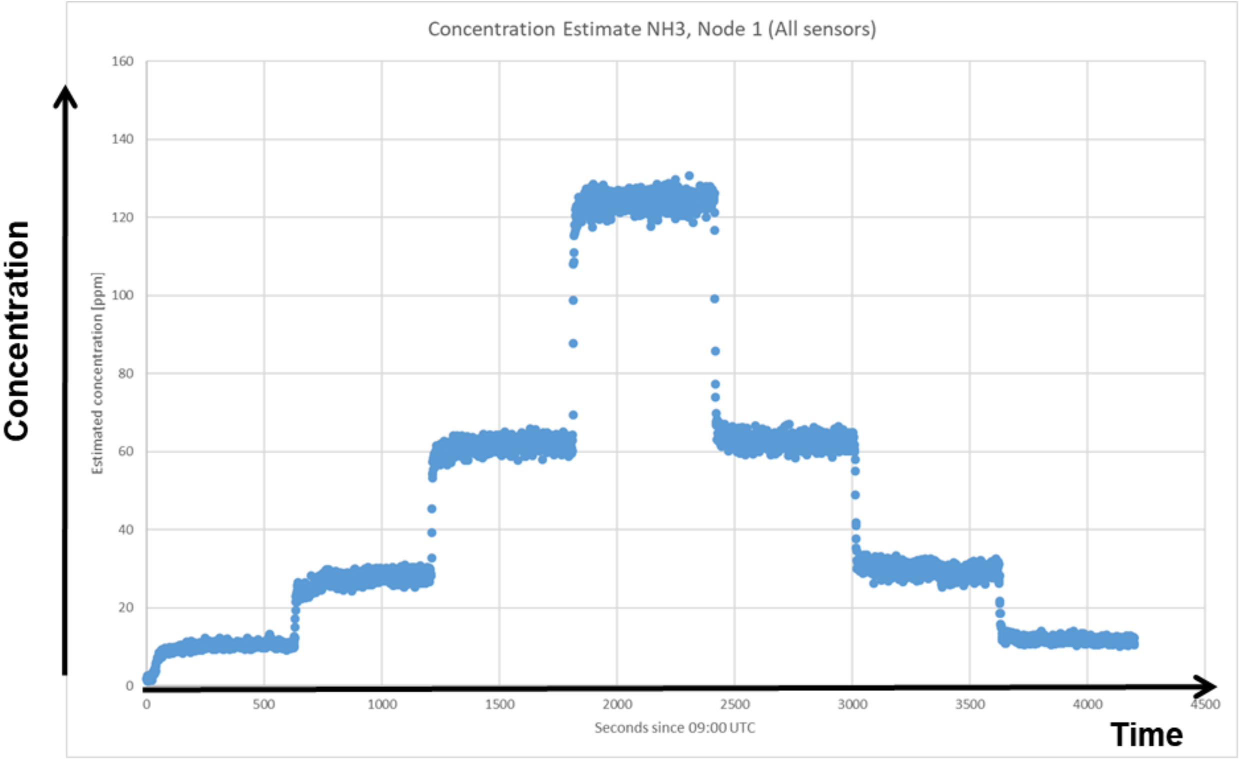


Figure 26: Example: Concentration estimate (All sensors; PID, FPD, IMS)

3.6.4 Normality Detection

During the Response Phase monitoring of the incident, the area is necessary also to lift an alarm. Discussion during the project motivated some work on an approach to automatically detect if the situation is back at a safe/normal level (as an alternative to continuous concentration estimation).

We implemented a prototypical algorithm in EU-SENSE based on the same mathematical concepts as with the Anomaly Detection, i.e. a statistical distance-based approach. However, during review with recorded experimental data, we came to the conclusion that several of the relevant sensors suffer from memory effects after exposure to larger concentrations. This means that technically the sensor responses do not within a reasonable time (“minutes”) drop back to their usual levels.

While the distance-based approach is conservative in the sense that if “Normality” is detected it is almost sure that the situation is safe again, its applicability is limited due to such memory effects. Therefore, we propose to always use concentration estimates in addition to such an approach.

3.7 WP6 Situational Awareness

3.7.1 Overview/Introduction

Main objectives:

- To develop a solution for enhancing situational awareness based on the network of sensors data
- To develop an algorithm for threat source estimation based on backward dispersion modelling
- To develop hazard prediction solution based on forward dispersion modelling
- To implement a Situational Awareness Tool that will be able to integrate all of the data produced by other components and provide a user interface
- To implement Training/Simulation mode Tool

This work package covers the development of several of the core software components powering the EU-SENSE system. The work was carried out mainly by FOI and ITTI with valuable input from other consortium members. Three main components were developed: The Situational Awareness tool (SA-tool), the Source Location Estimation (SLE) Tool, and the Hazard prediction (HP) tool. The SA-tool integrates the data and results from all the other EU-SENSE components and presents it to the end-user. The SLE tool estimates the most probable source location (and amount) for the detected chemical release based on the concentration measurements from the EU-SENSE sensor nodes and meteorological data. The HP tool predicts both the current and future dispersion of the chemical in the air based on a source term and meteorological data. These results are used by the HP tool to determine which areas are safe and areas where the air concentrations will reach dangerous levels. These components are designed to operate in two modes: “operational mode” where they are working on a real ongoing situation with live data, and “training mode” where the system operates on recorded or simulated data for training purposes. As part of WP6 FOI also conducted a successful field trial, consisting of controlled releases of several different substances, to collect air concentration data under real-life conditions. This data has been very useful for testing and validation of the source estimation algorithm as well as other aspects of the EU-SENSE system. This field trial was the first real test of the full EU-SENSE sensor network.

3.7.2 Dispersion Calculations

Both the HP and SLE-tool rely on the ability to perform atmospheric dispersion calculations. Dispersion calculation is needed both forward in time for hazard prediction and backward in time (so-called inverse dispersion calculations) for source estimation. All dispersion calculations were performed using the Dispersion Engine (DE) which is a computational framework developed at FOI. DE is designed as a bridge that can connect several different types of models into one combined simulation. Typical use cases would be connecting a source model (describing e.g. an accidental or intentional release of a harmful chemical substance) with an atmospheric dispersion calculation, which in turn feeds an effect model translating the results into potential health effects for the exposed population.

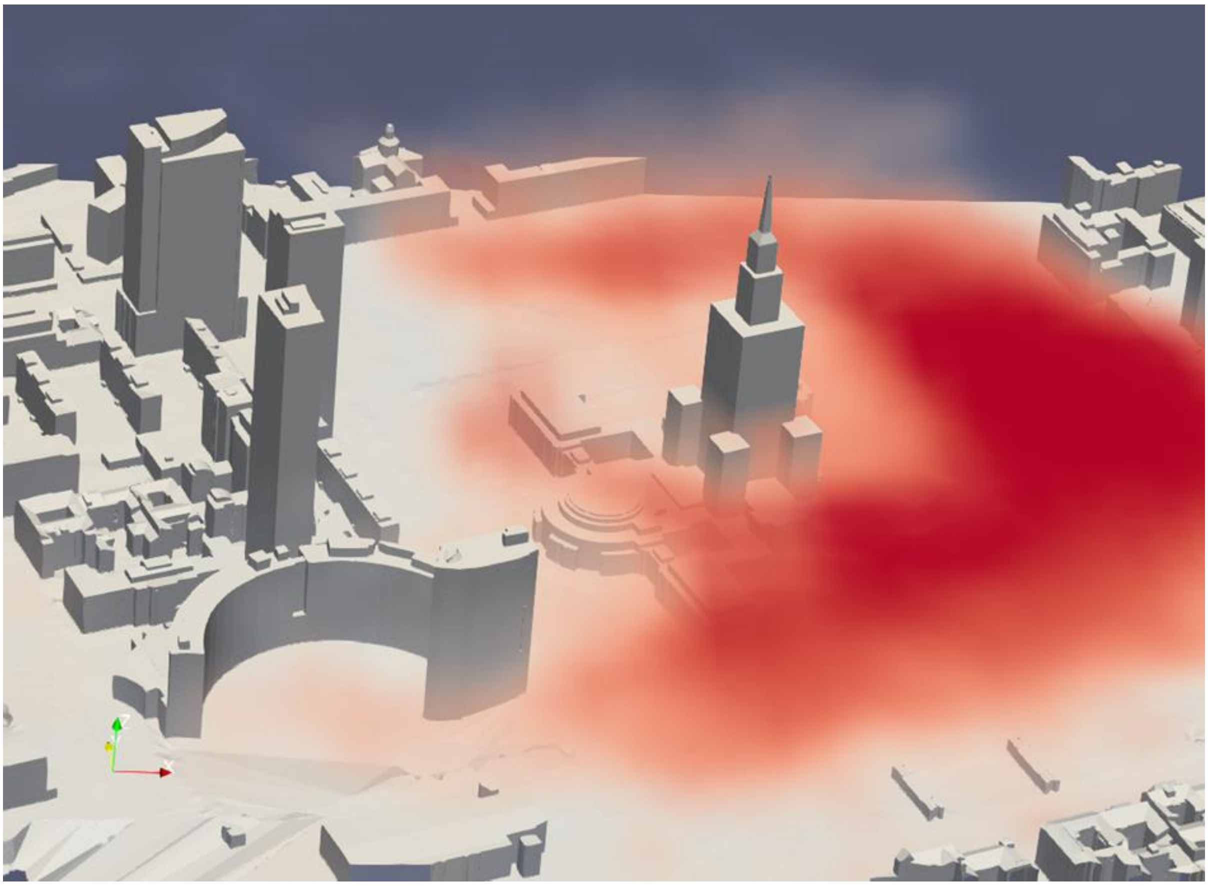


Figure 27 Full 3D simulation of air dispersion of a harmful substance around the Palace of Culture and Science in Warsaw. Simulation performed by the new UPELLO dispersion model in DE

For the standard case of flat terrain, which is what most have been considered within the scope of the EU-SENSE project we use the well-tested LPELLO dispersion model in DE, which is a stochastic particle model using Langevin dynamics [20][21][22]. This is the model that was used during the final demonstration. To handle full 3D terrain, FOI has implemented a new dispersion model, UPELLO, that works on complex 3D terrain and supports full 3D wind fields. This model is intended to increase the accuracy of dispersion calculation in urban environments. The model uses Lagrangian dynamics to propagate particles representing the pollutant on top of a wind field computed using CFD [22]. This model is fully operational within DE, see Figure 27, but since the model was completed at a late stage of the EU-SENSE project, and therefore not fully utilized and tested with the rest of the EU-SENSE system, it was not used at the final demonstration. For the scenario, at the final demonstration, it was also our view that the LPELLO model was sufficient. Research done at FOI as part of the EU-SENSE project regarding this model was recently published as an article in the peer-reviewed journal *Atmosphere* [23]. Figure 28 shows an example of a 3D wind field obtained using the CFD RANS solver together with the concentration field originating from a chemical release at the point marked with a star at the lower edge of the image. Buildings and streets have an important effect on the observed flow patterns and the resulting dispersion of the substance.

In the EU-SENSE system, the SLE and HP tools are designed as independent servers running DE internally. To access them, the SA-tool connects remotely and sends the relevant commands and data to the SLE and HP-tools which in turn performs the calculation and respond with the resulting source estimates and hazard predictions. All communication between the HP-, SLE-, and SA-tool is done over TCP/IP using the ZeroMQ communication library.

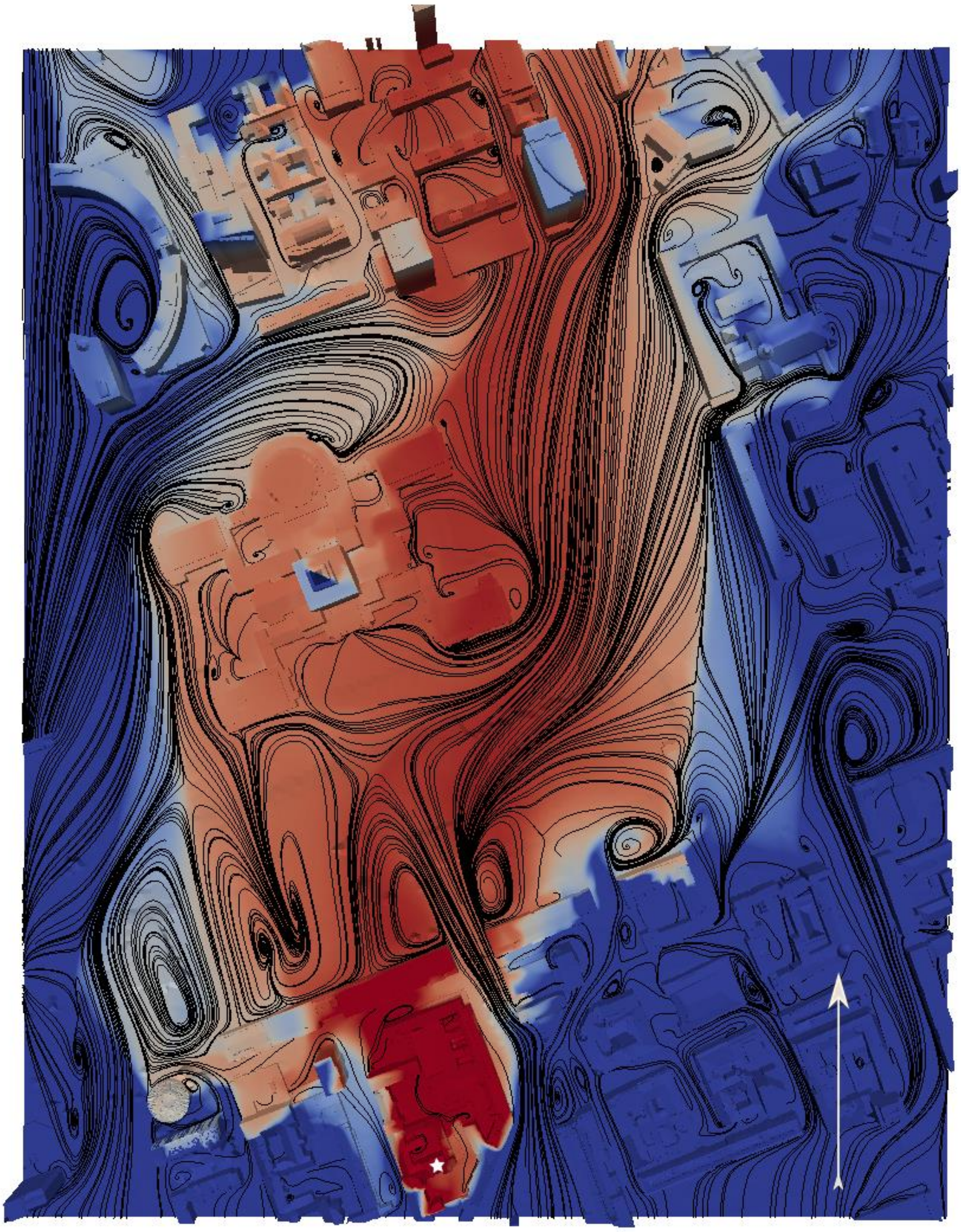


Figure 28 Top-down view of a full 3D simulated dispersion calculation around the Palace of Culture and Science in Warsaw. The colour indicates the ground-level air concentration and black lines indicate streamlines.

3.7.3 Source Estimation

Source estimation is a complicated problem where one tries to estimate the location and magnitude of a chemical release based on downwind sensor measurements. The basic approach used is to trace air parcels arriving at the sensors backward in time using the available meteorological data. The source is found by tracing parcels from several sensors backward in time and to estimate at which previous time and location they converge. Due to the many uncertainties involved in the process, measurement errors, incomplete meteorological data, turbulence, and limitations of the dispersion model, these parcels will never converge at one precise time and location in the past. Instead, we are forced to consider a much larger area of potential source locations and select the optimal source location based on some optimization criteria. This optimization procedure can be performed in many different ways with varying degrees of success. A significant part of WP6 was dedicated to investigating these issues and determining the preferred method to use. The findings were presented in Report D6.1 [24] which specifies the algorithms used in the SLE tool.

Figure 29 shows a simplified block diagram over the source estimation algorithm as implemented in the SLE tool indicating the main components as well as their input and output. The loop shown in the block diagram is an internal optimisation process that will converge after a few iterations to the optimal source parameters for the given sensor readings and meteorological parameters.

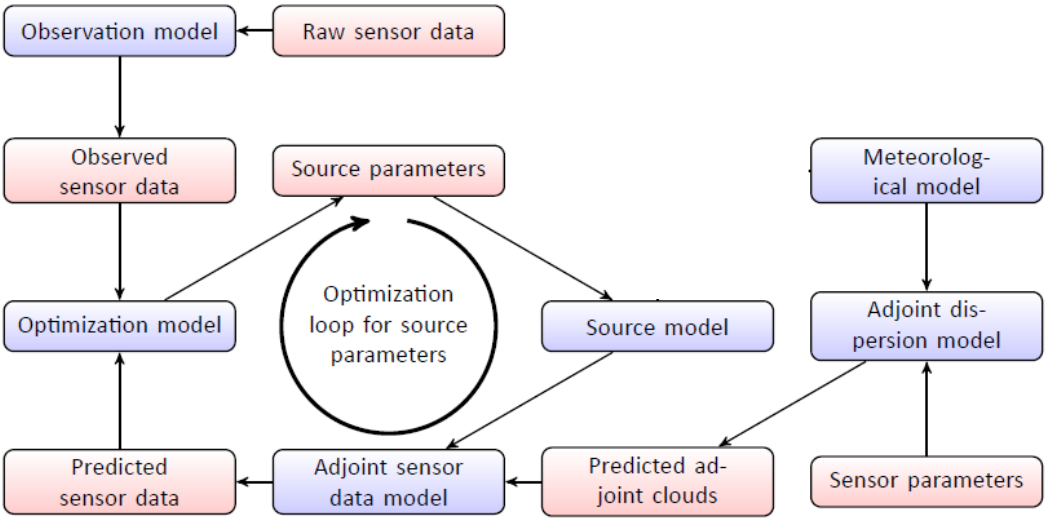


Figure 29 Block diagram of the source estimation process as implemented in the SLE-tool

3.7.4 Hazard Prediction

The main idea for hazard prediction is to predict the future dispersion of a substance from a given source term by running a normal dispersion calculation forward in time. From the dispersion calculation, we produce concentration fields describing how the substance is distributed and what air concentrations to expect at a given position and time. Once the concentrations are known the health effects have to be evaluated based on the toxicity of the substance in question. For EU-SENSE the potential hazard is based on the 10-minute AEGL exposure limits developed by Environmental Protection Agency - EPA[15] in the USA. Areas, where the concentration is above the AEGL-thresholds, are marked as hazardous and coloured to indicate danger in the graphical user interface. This measure is easy to calculate and can quickly mark areas as hazardous to help first responders decide which areas to avoid. However, this is a very simplified measure, and if one is interested in better quantifying the potential health effects of exposed individuals one should use a time-integrated quantity that better captures the cumulative toxic load as the cloud passes by.

Compared to source estimation the forward dispersion calculation required by the Hazard prediction is a much simpler and better-understood process as can be seen in the block diagram shown in Figure 30.

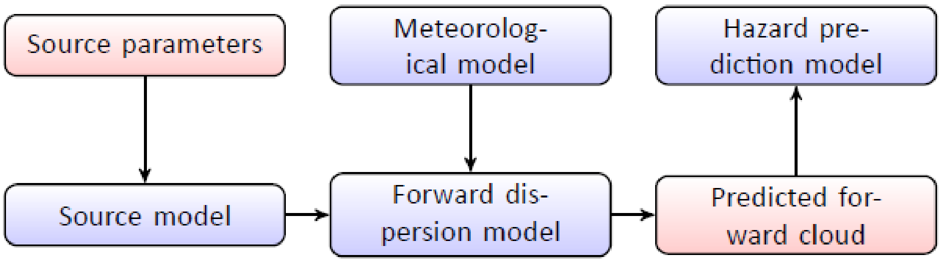


Figure 30 Block diagram showing the workflow for a simple hazard prediction from a known source.

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[15] Acute Exposure Guideline Levels for Airborne Chemicals | US EPA

When the HP-tool is run together with the SLE-tool, the source estimates from the SLE-tool are automatically forwarded to the HP-tool, which then triggers an automatic hazard prediction calculation. Figure 31 shows a block diagram of the combined system.

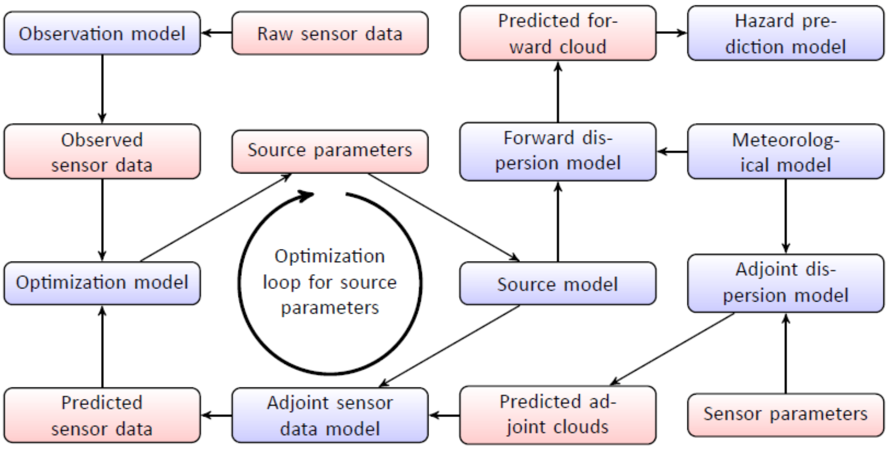


Figure 31 Block diagram showing the combined system SLE+HP-tool

Apart from producing hazards predictions based on the AEGL-levels, the HP-tool also produces raw air-concentration fields which can be useful for visualizing the plume, especially in cases where the release is weak and might not reach the AEGL-levels needed to obtain a hazardous region in the output.

Finally, the HP-tool can also generate synthetic sensor data for a given source term. This is used to prepare pre-recorded scenarios that can be used in the training mode.

FOI Field Trial

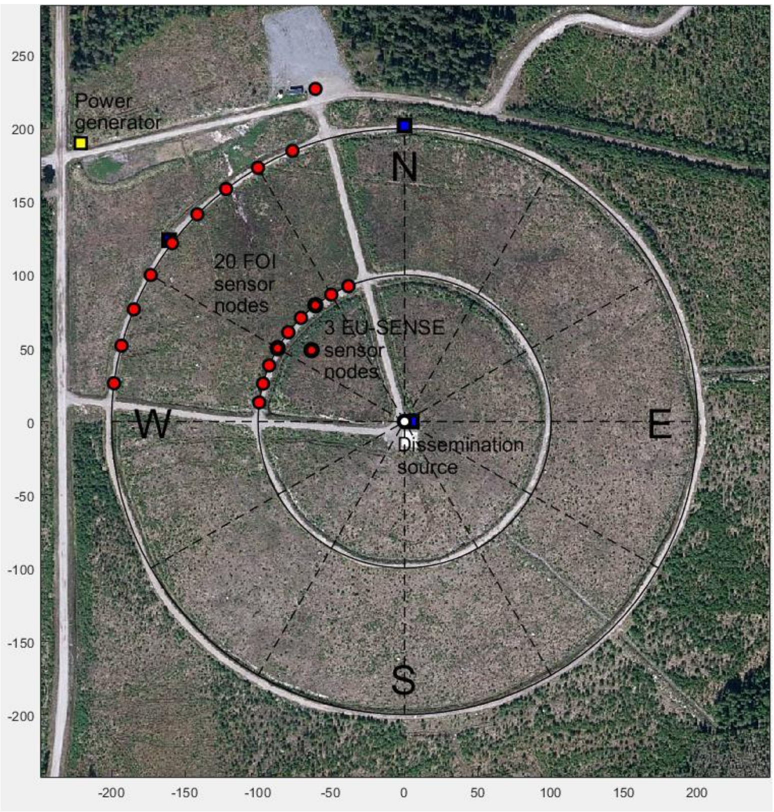


Figure 32 Aerial view showing the layout of the test site and positioning of the sensor nodes. The circular roads are positioned at 100 and 200 meters from the central point where the release took place. Photograph obtained from eniro.se.

In June 2020, a field trial was conducted by FOI at a military test site outside of Umeå, Sweden. It was a very useful first test of the EU-SENSE nodes under real conditions and the data and experiences obtained from the field trial have been used to test several components within the EU-SENSE project. For WP6 the main purpose of the test was to obtain the necessary data needed for testing and validation of the source estimation algorithm.

The test was conducted at a military test site managed by the CBRN Defence Centre of the Swedish Armed Forces. An aerial photo of the site can be seen in Figure 32. This location is very good for this type of test as it is possible to obtain permission to perform relatively large releases of selected substances. In total, the field trial consisted of 13 controlled releases conducted over three days. Nine of the releases were made using ammonia, while the remaining four releases were made using different substances (harmless substitutes) for chemical warfare agents intended to test the ability of the EU-SENSE nodes to detect and identify these substances. This was also a good test of the EU-SENSE node design, as it tested the ability of the nodes to communicate, save, and transmit data during a live event.

The sensor nodes used during the test were the three prototype EU-SENSE nodes. In addition, FOI's sensor network consisting of 20 nodes was applied as well. Having access to data from a large number of sensors was essential for evaluating the source estimation algorithm, and the use of two separate sensor networks allowed for interesting comparisons and cross-validation of responses between the FOI-nodes and the EU-SENSE nodes. Due to the large amount of data generated by the FOI sensors, a full analysis has not yet been possible. We expect that the work of analysing the field trial data will continue at FOI after the official conclusion of the EU-SENSE project. Some preliminary analysis can be seen in Figure 33, here the sensor data from one of the releases during the field trial have been fed through the SLE tool, the predicted source location is the yellow area slightly below the true source location. Results are very promising and constitute a good test of the SLE tool and the associated EU-SENSE components, especially considering that we are dealing with real sensor data.

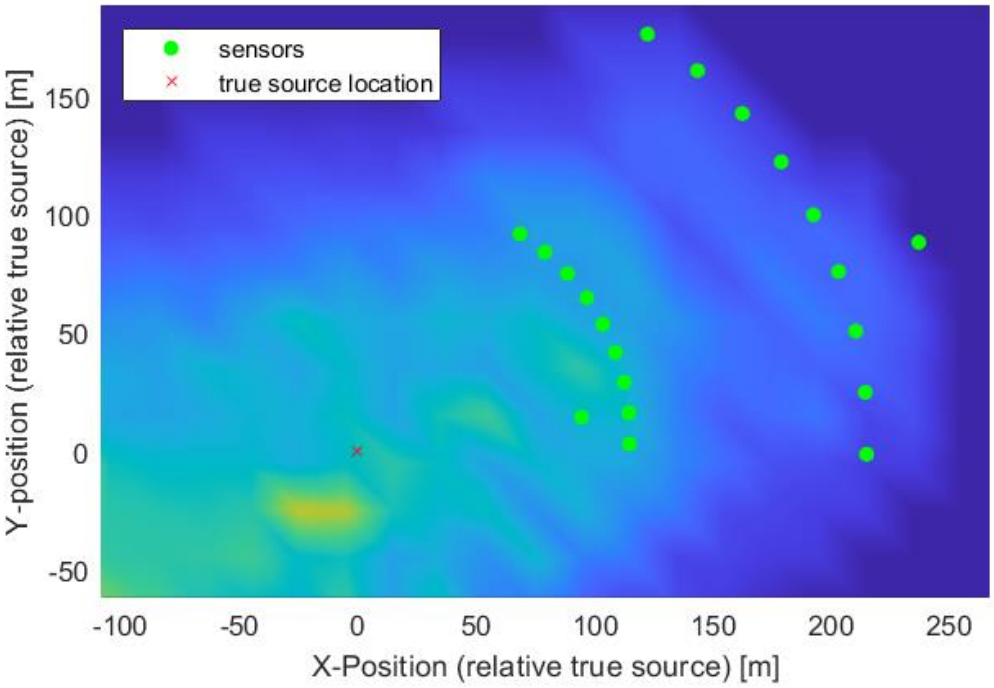


Figure 33 Heat map over probable source locations based on data from the FOI field trial. The yellow area indicates the likely source location as predicted by the source estimation algorithm.

3.7.5 Situational Awareness

The main purpose of the Situational Awareness (SA) Tool is to provide an access point for the user to the EU-SENSE system. SA Tool is divided into two parts: backend core server and frontend GUI application.

Network controller
Identifier: test-network-controller-1
IP Address: tcp://127.0.0.1:5572
Sensor nodes
Node #1
ID: node-1
Type: STATIONARY
Sensors:
Node #2
ID: node-2
Type: WEARABLE
Sensors:
Node #3

Status
Node #1
Status: not alarming
ID: node-1
Latitude: 52.448939
Longitude: 20.670656
Node #2
Node #3
Status: not alarming
ID: node-3
Latitude: 52.449439
Longitude: 20.670303
Node #4
Status: not alarming
ID: node-4

Nodes deployed: 5
System status: No threat detected
Current process: PREPAREDNESS

Node configuration
ID: node-1
Label: sensor node
Type: STATIONARY
Sensors: SRD, GDA-P PID, GDA-P EC

Node status
Status: not alarming
Latitude: 52.448939
Longitude: 20.670656

Detection status
Anomaly detected: false
Anomaly probability: Low

Figure 34 SA Tool – main view

The role of the SA backend is to integrate the data received from a set of Computational Tools (Source Estimation and Hazard Prediction), Environmental Noise Tool, and Network Controller. Additionally, the SA Tool backend connects the user with these tools so that the user could manually manipulate the system for example: manually request Source Estimation or Hazard Prediction calculations.

The role of the SA Tool GUI app was to provide a user with visualizations of the EU-SENSE system state, which consists mainly of:

- visualization of the configuration and state of the network of heterogeneous sensor nodes,
- visualization of the sensor nodes located on the Area of Interest (AOI),
- notifications about system errors,
- notification about the EU-SENSE system alarms,
- manual control of the system (raising alarms, adding threat sources, requesting Computational Tools execution).

Delay: 0 s
Nodes deployed: 5
System status: Manual alarm
Current process: SIMULATION

Figure 35 SA Tool – visualization of the hazard prediction

Communication between the backend server and GUI application has been implemented using MQTT (publish-subscribe network protocol) and as it was mentioned before ZMQ.

Situational Awareness software has been equipped with two different modes of operation: Operational mode and Training mode. The latter will be further described in the next chapter. In both of these modes, two types of users are available: Expert user and Responder user. The first has access to all of the previously mentioned functionalities. The Responder's functionalities, on the other hand, have been limited to include only the visualization of essential EU-SENSE network data without the ability to manipulate the system's state or configuration. Additionally, Responder has been equipped with a mobile view, which can be deployed on any mobile device such as a smartphone or tablet.

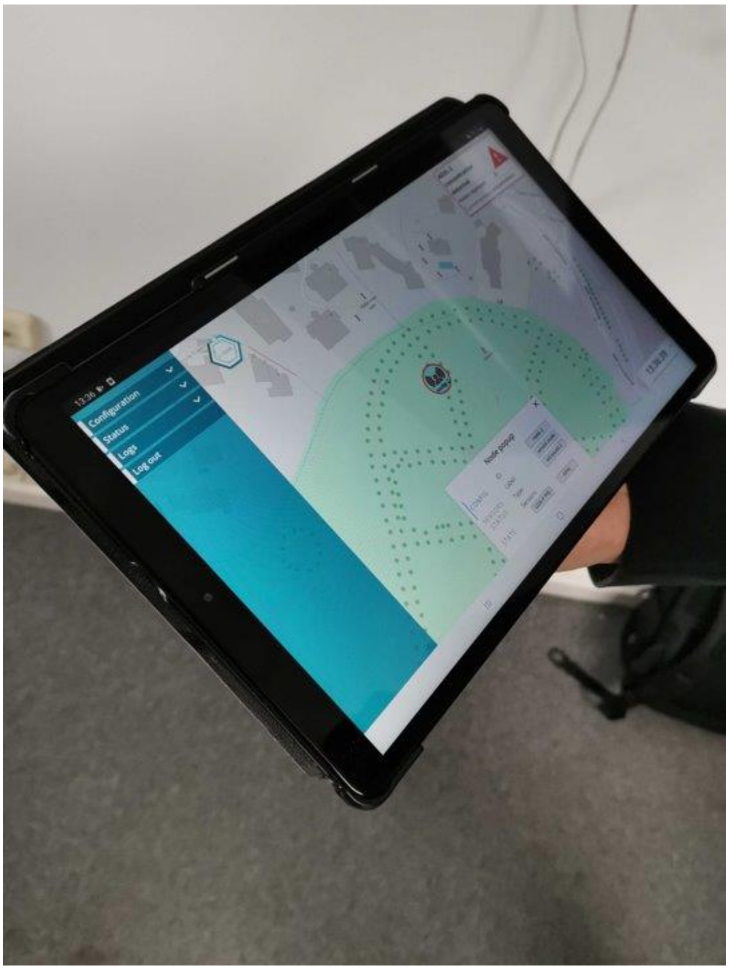


Figure 36 SA Tool – remote access via a tablet

3.7.6 Training Mode

Training mode is an EU-SENSE tool that is based on the SA Tool software. It was designed to equip first responders with a tool, which could be used for the training of the first responders and to showcase capabilities of the EU-SENSE system without the need of the actual chemical threat presence.

EU-SENSE Training Mode has been divided into two sub-modes: Simulation and Historical.

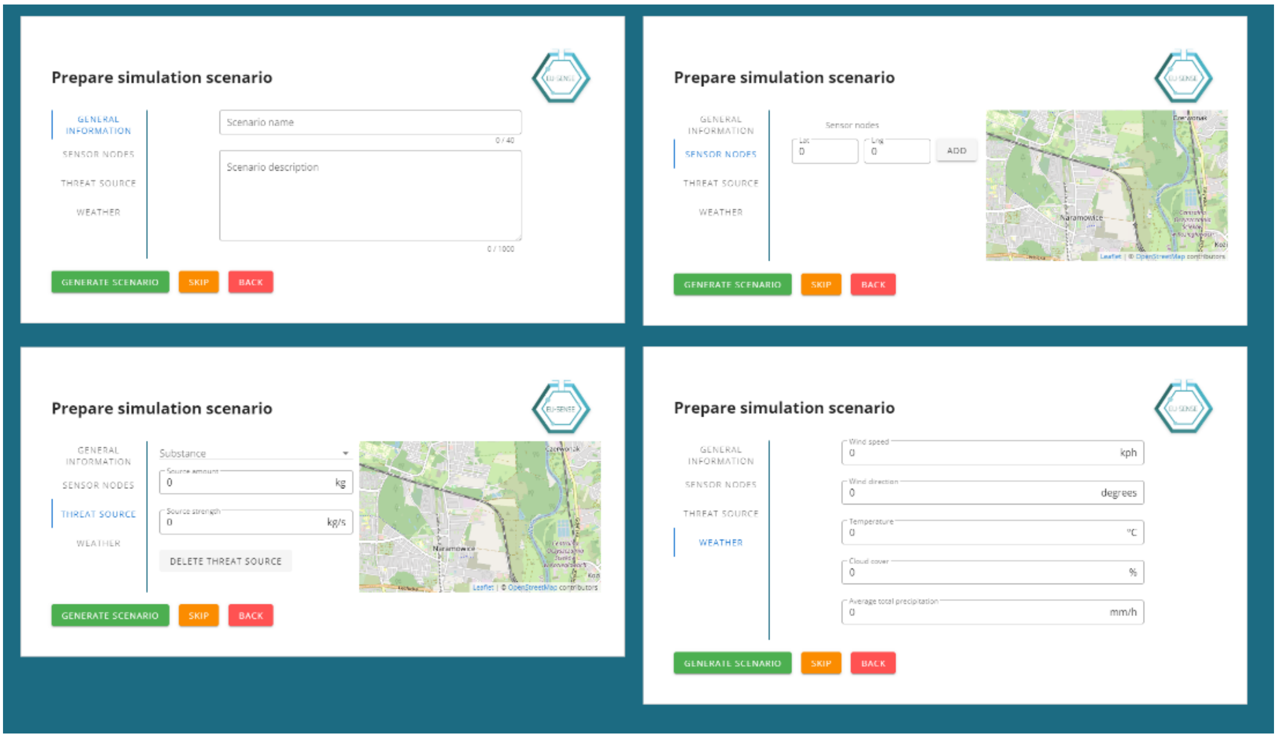
The first one, the Simulation sub-mode, enables a user to create an artificial scenario, which then can be run and controlled using SA Tool GUI input methods such as the manual request of the Computational Tools execution. Simulation sub-mode utilizes three additional training mode components:

- Synthetic Environment - region generated by the Hazard Prediction Tool based on scenario input such as region and weather. It stores information about contamination values in a selected area in a given time frame. The HP Tool is provided with an area that requires a prediction of contamination. The synthetic environment receives X (where X is many samples in time and duration of the simulation) of those areas, where each frame stands for one sample in time. Once the clock is started and the sensors start moving, then the readings would be different.

- Synthetic Sensor Node – mock-up of the EU-SENSE Sensor Node. It is responsible for producing artificial measurements based on data received from the Synthetic Environment.
- Simulation Loop – a process that mimics the behaviour of an operational EU-SENSE system. The data on which the Simulation Loop works is being fetched from the Mock-up database.

The scenario data has been divided into 4 major parts (see also Figure 37):

- General Information: Scenario name and Scenario description,
- Sensor nodes: latitude and longitude of the synthetic sensor nodes. The user can input up to 5 synthetic sensor nodes,
- Threat Source: latitude and longitude of the artificial threat source and chemical agent with its amount and the strength of the release,
- Weather: wind speed (kph), wind direction (degrees), temperature (°C), cloud cover (%) average total precipitation (mm/h).



Lat 0 Lng 0

Source amount 0 kg

Source strength 0 kg/s

Wind speed 0 kph

Wind direction 0 degrees

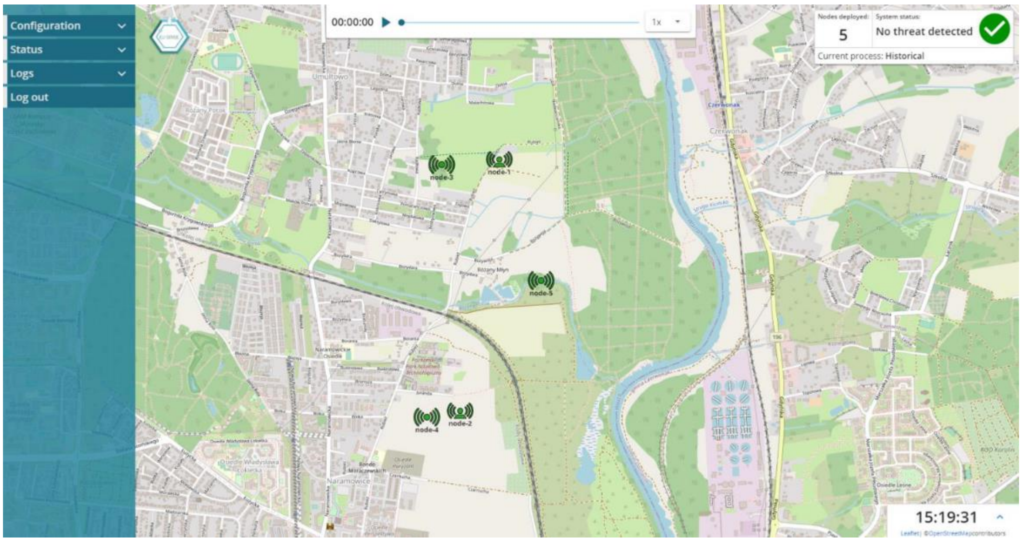
Temperature 0 °C

Cloud cover 0 %

Average total precipitation 0 mm/h

Figure 37 Training mode – scenario generation views

The second Training mode sub-mode – Historical sub-mode operates only on historical scenarios stored in the EU-SENSE database. It enables users to analyse previous cases thanks to the implementation of the playback component, which allows the user to play/pause a selected scenario, jump to different timestamps of the scenario and change the playback speed.



Nodes deployed: 5
System status: No threat detected
Current process: Historical
15:19:31

Figure 38 Historical sub-mode view

3.8 WP7 Integration and Validation

3.8.1 System engineering approach

The EU-SENSE system consists out of a Data Collection Layer, a Computational Layer, and a Network Management Layer. Each of those layers is designed and integrated for EU-SENSE. In this work package, the several components of the EU-SENSE system developed under WP4-6, based on the requirements as derived in WP2 and translated in the EU-SENSE architecture in WP3 are integrated with the system and validated against the end-user requirements. For integration and validation of the EU-SENSE system, the V-model for system engineering is used as an approach (Figure 39).

The V-model emphasizes requirements-driven design and testing. The requirements of the EU-SENSE system are based on the High-Level S&T objectives, which are derived from the ENCIRCLE project[16]. To build a system more detailed operational requirements are required. These requirements are derived in WP2 based on end-user needs [4].

The end-user needs have been translated into functional and non-functional system requirements. Those requirements are then translated into the EU-SENSE system architecture. The system architecture level is then used for integration tests with the functional and non-functional requirements as the input against which the integrated system is validated.

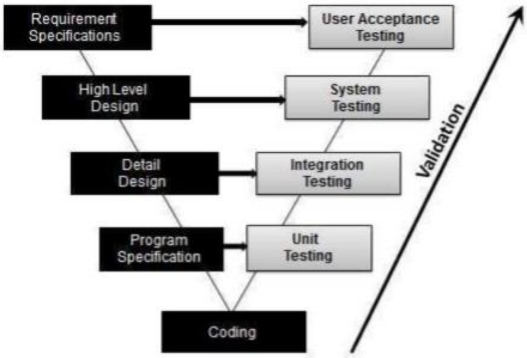


Figure 39 V model for system engineering

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[16] https://encircle-cbrn.eu/

3.8.2 Integration results

The integration of the EU-SENSE system was organised over three iterative integration rounds. The aim was to perform operational tests and experiments during and in between the integration rounds to serve as input for further optimization of the next iteration of the EU-SENSE system. After each cycle of integration and testing, an evaluation report was delivered as a deliverable under WP7.

3.8.2.1 Integration results round 1

The first round of integration focussed on the development of the data collection layer as well as the Computational layer. This started with the development of the sensor nodes that connected a series of 6 detection principles. Those principles are;

1. EC
2. IMS NH_3 doped
3. IMS H_2O doped
4. PID
5. FPD
6. MO-sensor array

The sensor node is the interface between the sensor systems and the node controller. The nodes provide a location and time-stamp to the measurement output of the subscribed sensors. The resulting data stream is then forwarded to the Network Controller that gathers data from all subscribed nodes and feeds this information to the various data processing tools that were still under development The goal was to produce a network of sensors that produced a reliable data stream in a binary format that is available only to the subscribed systems. A challenge the consortium faced during the integration of several sensors was the interfacing of sensor systems from several suppliers. The data output of detection systems are not harmonized over the industry and most of the system outputs are encrypted for security purposes. The presence of the main sensor supplier as a consortium partner appeared to be crucial in gaining access to not completely processed data. The work assumption of EU-SENSE is that full processing of the data will result in partial loss of information which may provide additional classification power once data is fused before complete processing.

For the Computational Layer, several tools were developed. The first was the Source Location Estimation Tool (SLET) that enables the system to use detection responses to estimate the location of a threat. This function was successfully connected to the Situational Awareness Tool (SAT) that assists the user with decision making via the later to be developed Graphical User Interface (GUI). The most critical tool that was to be developed is the Environmental Noise Learning Tool that uses machine learning algorithms to combine all sensory data to find anomalies in the environment. Due to a lack of sufficiently high-quality sensor response data this development was delayed. There were several causes such as technical issues that lead to unusable data sets and fewer measurement campaigns as planned. Corrective actions mostly focused on obtaining shorter iteration cycles were presented and implemented by the consortium.

3.8.2.2 Integration results round 2

In the second integration round, the computational layer was addressed as well as the network management layer. The Hazard Prediction tool and the Source Location Estimation tool were developed and tested as standalone tools. Severe delay in the realization of the Environmental Noise Learning tool was caused by a lack of sufficiently good quality data. To ensure good quality data for the development of the Environmental Noise Learning Tool additional integration tests were performed on the sensor node and the sensor node controller level.

The additional test concerning tests and evaluation on the equipment focussed on the ability to collect and store data streams on the sensor node and forward these to the Network Controller. Once the data collection was meeting the stability required, an effort was put into the development of the Environmental Noise Learning tool. The focus was on extensive data collection under several circumstances. A tool that was developed to help acquire good quality data was the Sensor Node Monitor. With this tool, the operator performing experiments could see if the node was gathering data. This resulted in time intervals of 5 hours without data loss and a strong reduction in iteration time since experiments could be repeated as soon as problems were discovered instead of waiting for data processing.

In the meantime, FOI worked on a system to estimate the source location of the system. To enable the development of the system a proper set of interface characteristics was determined and exchanged between the situational awareness tool development and the Source Location Estimation tool. The Source Location Estimation tool requires among others the location of the sensor node, the time-resolved identity, and concentration of compounds as well as the local meteorological circumstances. By having those parameters well described this part could be separately developed and integrated with the EU-SENSE system. To test the integration of the system dummy information was exchanged between the Node Controller and the Source Location Estimation tool.

Since the GUI was mostly developed, the next step in development was to make the connection between the GUI and the Situational Awareness tool. Now data received from the Environmental Noise Learning tool could be used to feed the other tools such as the HPT and the SLET. With dummy data, these tools could be evaluated.

Due to Covid-19 restrictions, a significant part of the planned measurement campaigns for the development of the Environmental Noise Learning tool was cancelled. The time for those campaigns has been used in an alternative way by further improving the hardware of the nodes, the sensor network controller, and by building an EU-SENSE sensor node monitor. Although a limited set of data was present for the development and validation of the tool a severe delay had occurred in the realization of the project since integration was already projected in the 2nd integration round. Additional data collection campaigns were planned for validation of the system in different environments and seasons. Development and integration of the Environmental Noise Learning Tool were anticipated to be reached before the scheduled postponed demonstration of the EU-SENSE system. To reach this point the consortium had asked the EU Commission to the extent the project by 6 months.

3.8.2.3 Integration results round 3

In the third and final integration test approach, the complete system had to be integrated and tested against the architecture described in D3.1-D3.4 [17] [18]. The data collection layer was further developed. The system now uses a suite of sensors connected to three sensor nodes. The data collected on the sensor level is stored on the nodes and wirelessly sent to the Situational Awareness tool via a system network controller.

On the computational layer, three tools were integrated. The first and largest tool is the Environmental Noise Learning Tool. The tool is fed with the raw sensor data and processes the data to determine whether an alarm needs to be proposed. The first step is to determine a mathematical approach to determine anomalies in the recorded sensor signals. When the anomaly scores exceed a certain level the necessity to raise an alarm is forwarded to the SAT. Based on sensor response the classification protocol is used to select the most relevant set of chemicals that could be used for identification. Based on a developed library the best matching identity is fed to the SAT together with an estimation of the concentration by the developed Concentration Estimation algorithm. Together these pieces of information result in an alarm suggestion to the user in the GUI.

The GUI is developed in such a way that the user is asked to either manually accept (raise) or decline an alarm. With the ENLT working and presenting a more sensitive detection platform, other tools could be finally challenged with real data sets coming from the EU-SENSE system. The Hazard Prediction Tool and Source Location Estimation tools were able to receive data from the SAT and ENLT to perform the predictions that were needed by the user for decision making. Via the GUI the outcomes of these predictions were presented to the user in the form of either a representation of the area under threat or the estimated location of the source. Depending on the level of the user (commander/first responder) more or less information is presented on the GUI. This was considered an important requirement of the EU-SENSE system to not overload the user with information risking a less effective response.

All developed parts were successfully demonstrated in Nowy Dwor Mazowiecki on October 7th, 2021.

3.8.3 Validation approach

The integrated parts were validated against the user requirements developed in WP2 using an approach that was based on three different types of activities:

- Test
- Demonstrate
- Report

High influence requirements were tested. This means that the system was tested with sufficient quality measures to determine whether the system fulfilled the defined requirements.

For certain types of requirements, testing would be too time-consuming or the statistical evidence would not provide additional value for the validation of the instrument. Those requirements were then just demonstrated by a single occurrence where the behavior was registered.

The outcome of the validation was a series of three documents finished after each integration phase, that describe whether the system fulfills a requirement or not.

In case the system was not meeting a requirement, this could be a crucial or a non-crucial deviation. Crucial deviations were those deviations that endanger the realization of the overall project's requirements. For crucial deviations, additional action was necessary to meet the requirements. In the case of non-crucial deviations, additional action was considered optional.

The assigned action reflected the fact that certain defined features were desired by the end-user however they were not crucial to demonstrate the overall Science and Technology objectives as defined for the EU-SENSE project. Therefore, requirements were to be evaluated in the following way:

Is the requirement met?

- In case the requirement is met no further action is required.
- In case the requirement is not met, the following question is considered. Is meeting the requirement required to fulfill the EU-SENSE S&T objectives
    - In case the requirement is not met but required to meet the EU-SENSE objectives. A deviation from the original plan is discovered.
    - In case of meeting the requirement is required to meet the user requirements, but not required to meet the EU-SENSE objectives the corrective action is considered optional.

The above-described method resulted in an overview of outcomes (Table 3) for the evaluation of each requirement.

Table 3 Evaluation options EU-SENSE system

Status	Legend	Comment
O	Iteration optional	In the coming integration rounds, this aspect may be assessed to meet the requirements. Currently, this part is not integrated yet. However to address the high-level S&T objectives of the EU-SENSE project this requirement is not required. For the further development of a TRL 9 system, the requirement is considered optional.
FRAP	Future action Required, Action Planned (Integration phase 1 and 2)	In the coming integration rounds, this aspect needs to be assessed to meet the high-level S&T objectives of EU-SENSE. At the current integration stage of the system, this requirement however has not been assessed yet.
DR	Deviation to original requirements (3rd and final integration phase)	By the lack of future integration rounds, no option is available anymore to address those items to meet the derived high-level S&T objectives of EU-SENSE. A deviation from the original plan is discovered which prevents meeting the high-level S&T objectives.
NCAR	No Corrective Action Required	Requirement met. Future development to higher TRL might still need further development of the system on this requirement.

The evaluation of the requirement results-focussed not only on the extent to which a requirement is met but also on the further development steps that needed to be taken to meet the requirement in the next phase. In the case of the last report, the requirements are also challenged with the ambitious high-level objectives that could lead to a commercial system at the TRL-9 level. Some requirements are fitting for a TRL-6 system but need further development and validation to be applicable in a TRL-9 system.

3.8.4 Validation results

The previously described integration rounds ended with the validation step that was reported using the described approach. In the next section, an overview is given for the outcomes for the 147 requirements that were derived and worked on over the three integration rounds.

3.8.4.1 Validation results integration round 1

In this first period (until M21) the focus of the efforts has been on the development of the data acquisition layer of the EU-SENSE system. The data acquisition layer consists of the sensor node (Figure 40) and the sensor node controller. Of the sensor node, 6 out of 15 requirements were met. An additional 3 of 15 required additional modification of the system. The remaining 6 could optionally be modified to meet the set requirements.

Figure 40 Version (2nd generation) of the Sensor node at M21

The sensor node controller was in the early stage of development. Therefore the design still needed to address all requirements. 2 of the requirements against which is validated were considered optional since the foreseen product is TRL-level 5/6 where the requirements were derived for the final product at TRL-9.

The second layer of the EU-SENSE system was the computational layer. The computational layer existed of a Classification-, Identification-, Concentration Estimation-, Environmental Noise Learning-, Hazard Prediction- and the Source Location Estimation Tool. The computational layer was not integrated in the EU-SENSE system yet. However, even in this early stage of the project 4 requirements were already met. 34 requirements still needed to be addressed during the implementation. An additional 5 requirements could be optionally addressed.

The third layer of the EU-SENSE system was the Network management layer. This layer consists of the Training Component, the GUI, and the Situational Awareness Tool. The development of these tools has hardly been addressed in this phase of the project. 46 requirements still needed to be addressed in the coming two iteration/integration rounds. An additional 5 requirements were considered optionally.

Also at the system level general requirements were derived against which the system is validated. Those requirements were currently hardly assessed since the integration of the general system was still in an early stage. In total 29 requirements were evaluated of which 20 still required attention during the integration and implementation of the system. An additional 9 requirements were considered optionally.

Since the consortium had experienced severe setbacks in the composition phase of the nodes as well as by transporting the dual-use components between the consortium partners in the various nations. The consortium needed to optimize its remaining time in realizing the high-level S&T objectives which were prioritized above the optional requirements.

In total 147 requirements were evaluated. Out of the 147, only 10 requirements were met. 20 requirements were considered optional in this phase. The remaining 108 requirements were foreseen to be developed in the next two integration phases.

3.8.4.2 Validation results integration round 2

The second integration period focused less on hardware development. Since the connection between the sensors and the node was already built only optimization of the hardware was performed resulting in a new version of the Sensor node (Figure 41) that has incorporated the findings that were encountered after the first integration phase. This is considered a nice example of the iterative process that took place between the first and second integration phases.

Figure 41 Updated version of the Sensor node (3rd generation)

The sensor node and the Network Controller had achieved almost complete functionality. Other parts especially the components required for the classification, identification, and concentration estimation still required a significant effort. The development of the algorithms required for the functionality of the EU-SENSE system however had severely suffered from the limited possibilities to perform measurement campaigns due to lockdown restrictions over Europe due to the COVID-19 pandemic. This resulted in a minimum dataset that was recorded for the derivation and implementation of those building blocks. The data was acquired in the last weeks of this integration period so the development of the algorithms was just started during the evaluation of the requirements. Therefore processing and validation of the derived algorithms were still required to provide this part of the system on the required level.

The algorithms for the Source Location Estimation Tool and the Hazard Prediction Tool were not implemented in the EU-SENSE tool yet, however, the algorithms were already been tested on independent datasets. Therefore the successful implementation of those tools in the 3rd integration round was expected to be achieved before the final demonstration of the project.

The Graphical User Interface, as well as the Situational Awareness Tool, still required a serious effort to reach the required end state. However successful implementation of those building blocks was anticipated feasible since end-user meetings to test mock-ups resulted in a positive response. Therefore the successful implementation of a well-developed graphical user interface, as well as a proper functioning situational awareness tool, were deemed feasible.

The required training component still required a lot of effort, however, this work was planned at the end of the development anyway, since for this effort a finalized implementation of the system is required.

The consortium needed to optimize its remaining time in realizing the high-level S&T objectives which were prioritized above the optional requirements. A first step in the mitigation actions partially based on the selected V-model integration approach was the contingency plan which was accepted by the EU for extension of the project by 6 months.

Again in total 147 requirements were evaluated. Out of the 147 in total 41 requirements were met which shows a big step forward. 28 requirements were considered optional in this phase. The remaining 78 requirements were foreseen to be developed in the next and final integration phase.

3.8.4.3 Validation results integration round 3

The development of the EU-SENSE system has reached the end state of this project intending to deliver a TRL 6 product after three iteration phases. The user requirements as defined with the end-user community in the first phase of the project together to line up with the needs of the ENCIRCLE project resulted in a series of ambitious high-level S&T objectives of the project. Each requirement was therefore not only evaluated with the TRL 6 end state of this project in mind but also to what extent they could meet the final TRL 9 end state of a commercial product.

Since the project is at its end, no further iterations will be made within the current project. The evaluation status FRAP (Future action Required, Action Planned) is therefore not present in this last update of the requirement evaluation outcome. Mostly used is the NCAR assignment that tells a requirement at least meets the TRL 6 state but in most cases even the higher S&T objectives. For future development to a higher TRL, it could still be necessary to perform an additional iteration of the requirement. Some requirements are considered optional and are directed on requirements that ensure optimal performance to the end-user, but are not required to establish the high-level S&T objectives of the project. A new outcome that was added to the evaluation is the DR (deviation to original requirement). When assigned the outcome is an attempt to meet the high-level S&T objectives but no more iterations are needed to fulfil the requirement. Often at the concept level, a solution works but more refinement or supporting (experimental) data is needed to fully meet the requirement.

Technically, the sensor nodes and NSC have achieved complete functionality at the TRL 6 level (Figure 42). With this outcome, the data collection layer of the EU-SENSE system is considered to be finished. Future efforts could be made to make the system more robust and easy to set up which are typical development phases to improve the system to TRL 9.

Figure 42 Final set of three sensors nodes as demonstrated in the training facility in Nowy Dwór Mazowiecki

Major steps have been made in the computational layer of the EU-SENSE system during the final iteration phase. Both the required input functions such as identification and concentration estimation as well as the required tools to assist the user in the decision-making process such as Hazard Prediction and Source Location Estimation have been successfully integrated into the system. Their functionality has been proven and presented during the live demonstration(October 2021) in Nowy Dwór Mazowiecki. As only a limited amount of experimental data was available for the development of these functions some tools require more refinement when the EU-SENSE system needs to be upgraded to TRL 9.

The network management layer is most focused on making the system useable by the end-user. That means a Graphical Interface (GUI) that is easy to use, shows clear and limited information to the user at its corresponding user level (commander vs the first responder), and visualizes the current live situation to create optimal situational awareness. The EU-SENSE system now presents a GUI that meets these requirements and therefore fits the needs of the end-user. The usefulness of the GUI in combination with the Situational Awareness tool for the decision-making process is considered to be at a higher TRL level than TRL 6 and has therefore exceeded the minimum outcomes of this project. This applies also to the training mode that has been integrated to simulate scenarios (both playback and user-defined) and as such train the end-user in using the EU-SENSE system.

Again in total 147 requirements were evaluated. Out of the 147 in total 130 requirements were met. 15 requirements were considered optional for the delivered EU-SENSE system. The remaining 2 requirements were considered to be a deviation of the proposed requirement. Altogether it can be concluded that the final version of the EU-SENSE system meets almost all requirements at least to TRL 6 level. To upgrade the system towards TRL 9 requires mostly an effort in obtaining sufficient experimental data to further refine the developed tools. The provided suggestions for future improvement are all deemed achievable and could most likely lead to a commercial product.

3.8.5 Outcomes of the selected approach

The chosen system engineering approach based on the V-model resulted in a structured way of managing the user defines requirements and high-level S&T objectives towards requirements that could be monitored throughout the three integration phases. The chosen evaluation method based on the evaluation of each requirement after every integration phase gave a clear picture of the progress made and the tasks to be performed for the next integration step. An example of such development phases for the Sensor Node Controller can be found in Table 4. In this table after each of the integration phases, a larger number of requirements was met until after final integration all requirements were met apart from a single optional requirement.

Table 4: Development status sensor node controller related to relevant requirements

Requirement code	Status 1st integration phase	Status 2nd integration phase	Status final integration
TR_NSC_FR_001	FRAP	NCAR	NCAR
TR_NSC_FR_002	FRAP	NCAR	NCAR
TR_NSC_FR_003	FRAP	FRAP	NCAR
TR_NSC_FR_004	FRAP	NCAR	NCAR
TR_NSC_FR_005	FRAP	FRAP	NCAR
TR_NSC_FR_006	FRAP	FRAP	NCAR
TR_NSC_NF_001	O	O	O
TR_NSC_NF_002	O	O	NCAR
TR_NSC_NF_003	FRAP	NCAR	NCAR

Not only gave this approach a clear picture of the pending state of development but it also was used to determine where corrective measures were needed, especially when project delays occurred. The outcomes were for example used for the development of the contingency plan [1]. For a project like EU-SENSE, that has a high development focused series of objectives, this approach has therefore been considered very useful.

3.9 WP8 Training and Demonstration

Work Package 8 titled “Training and Demonstration” aimed to demonstrate EU-SENSE in operational conditions, to validate capabilities, properties, and correspondence of the proposed solutions with the overall objectives of the project, and last but not least to evaluate the EU-SENSE system from two perspectives: managerial and operational. Tasks carried out in WP8 were divided into two parts:

1. T8.1 Training Session resulted in D8.1 Training materials and session report was delivered;
2. T8.2 Final Demonstration resulted in D8.2 Demonstration Report and D8.3 Test Report on the Capabilities of Beyond the State-of-the-art CBRN Detection.

Moreover, these tasks complied with the EU-SENSE project S&T Objective 3: To provide novel capabilities for the training of CBRNe practitioners, answering the needs identified in the ENICRCLE catalogue. Especially those related to training. Firstly, to the insufficient training with the suitable equipment and its appropriate use. Secondly, to the lack of solutions dedicated to the training of people who are not familiar in detail with specialized activities in the field of CBRN.

Providing the necessary tools that supply a background for exercise is significant. Therefore, the EU-SENSE training module (see more in **Błąd! Nie można odnaleźć źródła odwołania.**) allows using simulations of scenarios reflecting the real situation related to the leakage of a hazardous substance during exercises, dedicated to first responders, as well as training on the cooperation of services during chemical events. The EU-SENSE system will allow supporting the process of training rescuers not only in the specialized level but above all in the primary one. The system is user-friendly and combines tools to support decision-making, both in the preparation and response phases.

In addition, two approaches were used:

- a **scenario-driven** approach: in dedicated training materials as well as during the final demonstration of the EU-SENSE;
- a **user-centric** approach: to support the personnel training process, a “Handbook of EU-SENSE System training mode” was provided.

The learning objectives of the training session relied on three questions. How to use the system? What are its counterparts? How to use a training module that is based on historical data? Moreover, the learning outcomes were grouped based on the necessary to be acquired: knowledge, skills, and personal competencies. Development of training materials, mainly the “Handbook of EU-SENSE System training mode”, was based on ADDIE methodology, containing such elements as analysis, design, development, implementation, and evaluation. During the analysis phase, a user-centric approach was applied by the collection of user requirements. Next, in the design phase, the draft of the training materials was proposed. The development phase consequently proceeded and the Handbook was created to help the future EU-SENSE system users in getting familiar with the system possibilities. Moreover, IT jargon was refined to be understood by a common user. The implementation and evaluation phases were, mainly, conducted during the final demonstration [25].

The final demonstration was organised to prove the EU-SENSE project realized high-level and S&T objectives set out in the proposal. It took place on the 6th and 7th of October 2021. The event was attended by representatives of all consortium partners, a stakeholder group consisting of representatives of the military, research institutes, institutions to counter-terrorism, emergency services, private companies related to CBRNe as well as other guests.

During the first day of the final demonstration, the presentations aimed to explain the complexity of CBRNe detection, to reveal existing problems in the related research, as well as to introduce the solutions developed in the project. The final Demonstration involved both theoretical and practical aspects. Regarding the theoretical part, it was primarily focused on the novelty of the EU-SENSE system, which lays mainly in the application of machine learning algorithms and dispersion modelling; detection of chemical substances; detection technologies and their improvement; modern computational tools; end-user perspective; as well as the Situational Awareness Tool and the training mode. The practical part relied on a showcase – one node with an integrated sensor. The participants, who took part in the Final Demonstration, represented the military, research institutes, end-users - counter-terrorism representatives, and private companies focusing on CBRNe topics. Moreover, the participants received the “Handbook of EU-SENSE System training mode”. The purpose of the handbook is to describe the EU-SENSE system functionalities and components. The first part of the document includes the description of hardware and software, while the second - describes training scenarios. The third part stands as a "step-by-step" tutorial on how to use the EU-SENSE system [26].

The second day of the Final Demonstration was held at the Base for Training and Rescue Innovation in Nowy Dwór Mazowiecki.

The Training and Rescue Innovation Base of The Main School of Fire Service (BSPiIR SGSP) in Nowy Dwór Mazowiecki is a professional training area with direct support and protection of firefighting officers and CBRNe equipment.

The specific objectives of BSPiIR SGSP include:

- Implementation of vocational education in all fields of study at SGSP,
- Use of the training ground as a place for the implementation of professional training for firefighters serving as a candidate in SGSP,
- Implementation of professional training for officers serving in SGSP,
- Researching the field of fire protection, civil protection, and rescue,
- Conducting joint exercises for entities of the National Fire and Rescue System, fire protection units, services of the Ministry of Internal Affairs, and national defense,
- Testing of equipment and extinguishing agents and extinguishing agents used in rescue operations,
- Testing organizational solutions increases the effectiveness of rescue operations,
- Unification of rescue operation techniques,
- Organization of training grounds,
- Securing an appropriate social base for all users of the proving ground base.

The action was simulated on the base of two, closely connected, reference scenarios (see more in 3.3.4). The first of them concerned a mass event and the second one regarded toxic industrial contamination. The scenarios were replicated during field exercises, which took place at a professional fire brigade training area.

Moreover, for a demonstration of the detection and identification capabilities of the EU-SENSE sensor network without releasing a huge amount of a specific chemical compound at the demonstration site, a dedicated experiment was conducted.

Demonstration results proved that the EU-SENSE system is properly implemented, works as expected in operational conditions, and achieved the required TRL. Involvement of guests and observers allowed to confirm its usefulness and value in two important dimensions. The technical dimension concerns technology innovation, integration of different detection technologies, and technological potential for further research. Special attention was put to data fusion and machine learning as well as to particular system elements (especially Node, Network Controller, Environmental Noise Learning Tool, Source Location Estimation Tool, Hazard Prediction Tool, and Situational Awareness Tool). Operational dimension related to EU-SENSE system usability for first responders’ entities facing CBRNe challenges and protecting the most important utilitarian values (human life and health). Based on reference scenarios facilitated to show the operational potential of EU-SENSE solutions and that they exceed functionalities of existing technologies used by the responders nowadays.

The final demonstration constitutes a serious step on the path to the practical implementation of EU-SENSE solutions in practice. End-users noticed that information from the system may significantly increase the operational potential of the response to CBRNe hazards by making first tactical decisions during arrival to the action and ad hoc adapting relevant decisions to existing, real safety conditions. Technical providers were made aware that involved technologies are characterized by sufficient potential to deal with technology transfer (from business to first responders) and further research categories [27].

3.10 WP9 Dissemination and Exploitation

Dissemination

The dissemination of the information on the project relied mainly on the project website and social media (Twitter, LinkedIn). Regarding the activity on the website, it was took place over the period from October 2019 to October 2021. The information was delivered in the form of News (over 50 posts, https://eu-sense.eu/news/) and Publications. The News reported on the activities in the EU-SENSE project and issues that resulted from the research and development process (e.g. possible scenarios in extremely hot conditions, training alignment with NATO documents, etc.) that were related to the project's activities. The Publications contained mentions about scientific articles, and presented topics on contemporary global challenges highlighting the importance of chemical detection. As for 28.10.2021, the EU-SENSE project website has reached a total of 70,010 visits from 20,639 visitors.

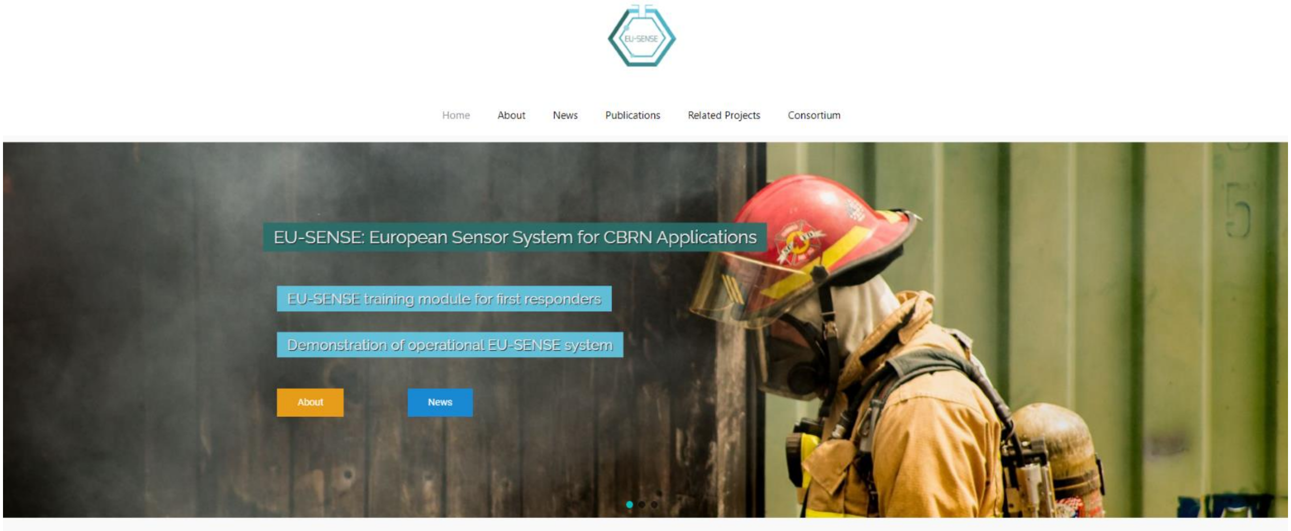

Figure 43 EU-SENSE Project website

In terms of social media channels, the EU-SENSE consortium utilised Twitter (269 followers) and LinkedIn (56 observers, 19 posts). Social media activity was also performed by consortium members through their individual accounts on Twitter, LinkedIn, and Facebook.

EU-SENSE
@eu_sense

Cutting-edge technology for detection of #ChemicalWeapon and #IndustrialChemicals threats

eu-sense.eu Joined May 2018

187 Following 268 Followers

Figure 44 EU-SENSE Twitter profile

The target audience in this dissemination activity was focused around academic representatives as well as project-related industry, private companies, services, and research institutes.

Apart from the abovementioned website and social media, the EU-SENSE project dissemination involved the following scientific publications:

1) Dobrowolska-Opała, M., Gudzbeler, G. (2019) European sensor system for CBRN applications, 9th International Defense and Homeland Security Simulation Workshop, DHSS 2019, pp. 16-22.
2) Dobrowolska-Opała, M., Gudzbeler, G. (2020) Selection of training methods in systems dedicated to detection of chemical hazards, 19th International Conference on Modeling and Applied Simulation, MAS 2020, pp. 172-176. Doi:10.46354/i3m.2020.mas.023
3) Szklarski, L., Maik, P., Walczyk, W. (2020) Developing a novel network of CBRNe sensors in response to existing capability gaps in current technologies. Proceedings of SPIE Chemical, Biological, Radiological, Nuclear, and Explosives (CBRNE) Sensing XXI (Vol. 11416, p. 114160Y). The International Society for Optical Engineering, 11416, art. no. 114160Y. DOI: 10.1117/12.2558044.
4) Elfverson, D.; Lejon, C. Use and Scalability of OpenFOAM for Wind Fields and Pollution Dispersion with Building- and Ground-Resolving Topography. Atmosphere 2021, 12, 1124. https://doi.org/10.3390/atmos12091124
5) Gawlik-Kobylińska M., Urban M., Gudzbeler G., Misiuk A. (2021) Simulation-based training in the use of the EU-SENSE CBRN reconnaissance device: a case study, Proceedings of the 11th International Defence and Homeland Security Simulation Worskhop (DHSS 2021) pp.40-47.
6) Urban M. (2021), Simulation in first-responders training to improve the decision-making process: chemical, biological and radiological weapons in improvised explosive devices at airports, Proceedings of the 11th International Defence and Homeland Security Simulation Worskhop (DHSS 2021) pp .54-62.
7) Kopp, N. (n.d.) EU-SENSE Data Fusion, Security and Defence Quarterly, [accepted].

As well as publications in professional journals:

1) Menary, P. (2020), European project aims to create a step-change in chemical detection, ESTTRAINING.

It should be emphasised that any peer-reviewed journal article is available in open access.

Apart from the publication activity, the EU-SENSE consortium members took part in the following conferences, workshops, and meetings:

1) International Defense and Homeland Security Simulation Workshop, DHSS 2019, 2021,
2) 19th International Conference on Modeling and Applied Simulation, MAS 2020,
3) the ENCIRCLE virtual end conference, 2021, https://eu-sense.eu/cbrne-state-of-the-art-virtual-event/
4) The Community of European Research and Innovation for Security (CERIS) Disaster-Resilient Societies (DRS) meeting (2021), https://eu-sense.eu/eu-sense-project-presented-at-the-community-of-european-research-and-innovation-for-security-ceris-disaster-resilient-societies-drs-meeting/
5) The International Conference on Military Technologies 2021 (The EU-SENSE project panel), https://eu-sense.eu/the-eu-sense-panel-at-the-international-conference-on-military-technologies-2021-overview/
6) 3rd International Conference CBRNE - Research & Innovation; 20-23 May 2019; Nantes, France,
7) The Emergency Services Show 2019, 18-19 September 2019; Birmingham, UK,
8) 21st International CBRN Symposium 2019; 12-13 November 2019; Farnborough, UK.
9) Spie Defense + Commercial Sensing 27.04-01.05, Online event
10) I3M: The 16th International Multidisciplinary Modelling & Simulation Multiconference September 2019, Lisbon, Portugal

11) UK National CBRN Forum, September 2019
12) Slándáil 2020: National Security Summit February 2020, Ireland
13) Eurosatory conference (Paris, France, 8-12 June 2018)
14) JRC Conference (Ispra, Italy, March 18, 2019)
15) CoU13 (Brussels, Belgium, 25-29 March 2019)

To promote the EU-SENSE project activities, the Special Issue on *Innovations for chemical, biological, radiological, nuclear + explosive – CBRNe defence* was announced at the Security and Defence Quarterly website: https://securityanddefence.pl/Special-Issue-Innovations-for-chemical-biological-radiological-nuclear-explosive,3093.html Papers are planned to be released in 2022.

Exploitation

The EU-SENSE project exploitation applies to the following results: training mode concept (exploitation form: paper to be published in a high-score scientific journal), simulation-based training scenario development (a set of scenarios included in the Scopus-indexed conference proceedings (DHSS) "Simulation-based training in the use of the EU-SENSE CBRN reconnaissance device: a case study"), engagement of stakeholders (via the EU-SENSE panel at the International Conference on Military Technologies 2021 in Brno, Czech Republic; the knowledge developed through the project was made available to stakeholders); general guidelines of the system design (in the form of a scientific paper, no limitations to apply and replicate the guidelines); engagement of stakeholders and academic representatives (Special Issue in the Security & Defence Quarterly - Innovations for chemical, biological, radiological, nuclear, explosive - CBRNe defence).

The results were used in further research activities - the training mode concept, scenarios, general guidelines of the system design were applied in the simulations; they served to develop a final product and were used in standardisation activities. Since implemented, they have contributed to the EU-SENSE system development. The project results give main advantages: direct – "know-how" on the training mode, system design, and scenario conduct; and indirect - improved safety and better-trained staff. Regarding the engagement of stakeholders, the public debates with researchers, academia, and potential end-users helped the consortium members identify real-world challenges and understand the use of emerging technologies for innovative solutions.

4 Critical Implementation Risks and Mitigation Actions

4.1 Foreseen Risks

No.	Description of risk	Work package(s) involved	Proposed risk-mitigation measures
Management risks			
R01	Problems with overall project progress.	All	Best practices and methods in terms of project management based on previous projects will be implemented. Moreover, regular monitoring of project processes with the focus on early detection of delays will be practiced.
R02	Meaningful changes in consortium e.g. partner resignation, change of crucial personnel	All	Project will be constantly monitored with solid involvement of the senior management of each partner of the consortium. Every partner has a strong commitment and has no objections as to the appropriateness of the project.
R03	Underestimation of resources for the task	All	Project will be regularly monitored in context of available resources for particular tasks.

No.	Description of risk	Work package(s) involved	Proposed risk-mitigation measures
R04	Difficulty in identifying the sufficient number of stakeholders covering all areas of knowledge related to the project.	All	In order to ensure proper selection of stakeholders and their field of expertise, Stakeholder Group will aid the identification process.
R05	Insufficient dissemination and exploitation activities.	WP8	Project partners envisage diversified dissemination activities including online activity (e.g. website, social media), conferences and workshops as well as open access scientific publications dedicated to various communities. Furthermore, successful dissemination exploitation will be guaranteed by end-users and identified stakeholders.
R06	EU-SENSE solution does not meet end-users needs and expectations	All	End-user and key stakeholders will be invited to requirements collections workshops. Their engagement will help identifying and prioritizing the most important ones.
R07	Deliverables from one WP are not available for other WPs on time	All	Regular contacts between WP leaders will be ensured. Project timeline and deliverable releases have been agreed by all WP leaders taking into account work to be done in particular work packages and its influence on other tasks.
Technical risks			
R08	Gap between proposed functionalities and critical functionalities	WP2	Early requirement analysis by stakeholder assessment
R09	Delay in sensor node development	WP5	Application of several types of sensors at several TRL-levels.
R10	Access to raw data of the instrument needs to be granted.	WP5	Developers are incorporated in the consortium to get access granted to the rawest data necessary.
R11	Minimum distance between sensor nodes requires more sensors than expected number of sensors	WP2, 5	Increased number of sensors to show feasibility of approach. In addition costs of used sensor nodes need to decrease.
R12	Raw data is too big to get transported to central node	WP5	Data compression will be applied if feasible and necessary.
R13	Fusion of the several technologies cause interface/fusion problems	WP5	More sensors of the same principle will be combined.
R14	Insufficient sensors available for background characterization	WP5	2-3 sensors of the same technology will be reserved for determining aerial correlation in signal.

No.	Description of risk	Work package(s) involved	Proposed risk-mitigation measures
R15	Background correlation characteristics vary per season and environment	WP5	Data will be recorded in such a way that time period to determine correlation and space correlation can be determined. Also the time period required to learn the behavior will be determined.
R16	Autonomous background collection at some locations might be difficult.	WP5	Collaboration with end-users from the onset of the project will guarantee access to sites, where detectors can be placed without the chance of tampering with the systems.
R17	Threat source estimation will require additional input.	WP6	Required input will be included in the technical documentation and the tool's specification will be delivered in the early stage of the project (as a part of technical requirements). Moreover, the iterative approach will provide initial feedback and possibility to adjust the tool design in case of any issues.
R18	System performance is lower than required by the end-users	WP7	The project plan assumes several iterations of the development activities. Tests and validation results (including feedback from end users) will impact the further iterations.
R19	No permission for the final demonstration will be given.	WP8	One of the partners within the consortium (SGSP) exploits the Polish professional firefighters training site. Hereby access for the final demonstration as well as the use of suited simulants is granted.

4.2 Unforeseen Risks

The below presented indicate risks that were unforeseen at the proposal phase.

Risk N°	Description of Risk	Related WP N°	Proposed risk-mitigation measures
UR1	Lack of access to internal sensor signal for further processing in the project.	WP4, 5, 6, 7	This risk emerged in the reporting period (M1-M12). Proengin declined access to raw data of AP4C. The risk mitigation action is carrying on the work with AP4C and using concentration data for EU-SENSE research.
UR2	Sensors are not available on time.	All	The delivery of sensors depends, to a large extent, on sensor manufactures. The delivery date, when delayed, bears impact on sensor adaptation (especially node development) and measurement session (T5.2).
UR3	Obtaining the agreement to ship sensor hardware outside EU.	WP5	Proengin, Airsense and TNO sensors are dual use items. Exporting them outside EU will require obtaining relevant export licence. This will be necessary in case of measurement session in Norway by FFI.

Risk N°	Description of Risk	Related WP N°	Proposed risk-mitigation measures
UR4	Late release of Sensor Node	WP4, 5	The schedule assumes the first iteration of the sensor node prototype at M16. This, however, may put at risk the measurement campaign carried out within WP5. Therefore, the effort will be put to release the early sensor node earlier for measurement campaign purposes.
UR5	Necessary data, like response characteristics or target substance library and sensor characteristics, not available to algorithm development or validation on time.	WP4, WP5, WP6, WP7	In order to minimize the risk, the data fusion block has been divided into several sub-functionalities and allocated to different partners. Therefore, by limiting the scope and identifying responsible partners, it is believed that delays will not appear.
UR5	Coronavirus pandemic. The COVID-19 pandemic influence all WPs of the project. The pandemic caused delays in different areas of the project. The most serious influence of the pandemic is the pause in measurement session. Consequence of this pause is the lack of sufficient dataset to continue work in WP5.	All	In response to pause in measurements, the consortium prepared a contingency plan to conduct additional measurement sessions. Formal Amendment of the project was accepted by the Project Officer and reviewers, which provided necessary time to conduct additional measurements, which generated sufficient dataset to finalize project prototypes.

5 Lessons learned

Lessons related to technical issues:

- Memory effects / contamination of sensors from larger concentrations can interfere with their usage especially during response phase (concentration estimation, unalarming).
- Large differences in response times of different sensors can limit their use in data fusion.
- Knowledge based data fusion techniques require reliable a-priori knowledge. If such information (e.g. from measurements) is limited, applicability of techniques like (Deep) Neural Networks or other pure data-driven methods might also be limited. Simpler methods like Bayesian Networks, in combination with other algorithms or manual preparation activities (e.g. model definition) can be a good alternative in such cases.
- In case extensibility of the network to e.g. new sensor technologies is a requirement, extensible methods of data processing and fusion are also necessary. Methods that are very specific for a technology are usually not well extensible.
- The above also applies to the use of raw sensor data. Processing at the network level (above sensor level) should ideally consume already slightly pre-processed data. This can allow to avoid unwanted

effects from sensor artifacts (e.g. micro-vibrations, sensor-internal switches etc.) and perhaps partially free the higher-level processing from calibration activities. However, it should be avoided that essential information gets lost during such sensor pre-processing.

- Not all investigated sensing technologies suffer from interferences of slowly changing environmental background, at least in the environments we considered.
- Coverage of larger areas with point detectors in a detect-to-warn scenario is difficult in particular for highly toxic substances, where already low concentrations can be dangerous. The use of standoff-detection as a fused information source could be worth of investigations.
- Situations with substance mixtures are a problem with the investigated sensing technologies. This can probably not be avoided completely (with these technologies); however, orthogonal fusion can help to improve the situation awareness in such cases. Automatic classification methods should target multiple binary classification problems instead of a single multi-class classification problem.
- Due to the high degree of uncertainty inherent to some of the investigated sub-functions, we find it useful to make this uncertainty explicit as a dedicated output.

Lessons related to management/administrative:

- The movement of equipment between partners is a slow and laborious process. Extra time should be factored in to take account of this.
- All data required for testing purposes should be decided and agreed upon at the outset of the project. This will help with time management and provide enough time for data collection. This is key to the success of the project and should be given sufficient time within the detailed plan at the beginning.
- More frequent meetings (even online) should be held to allow constant communication between partners. This will help relieve pressures on any partner in need of from others.

6 Conclusions

To conclude, this report summarises the work performed in the entirety of the project’s duration (M1-M42). As proven above, the EU-SENSE project consortium has managed to deliver all of the initial assumptions promised in the proposal (combined with necessary data fusion algorithms) by meeting all of the initially set milestones, which has resulted in providing an operational system on TRL-6 from scratch.

The system itself has been tested in both controlled, indoor conditions, as well as real-life, outdoor operation performed during the final demonstration of the project where both the system as a whole and each of its individual components have performed in a way that meets the required standards and a set of technical requirements.

This document has been divided into 6 sections that are providing insight into the methodologies used in the research and development process throughout the project’s lifetime as well as a detailed report on the work performed in each of the Work Packages. Furthermore, this report also touches on the critical implementation risks that the consortium has been faced with and discusses the mitigation actions undertaken to solve them. Finally, this document provides a summary of all the lessons learned by the EU-SENSE consortium during the 42 months of work performed in the project.

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SEC-05-DRS-2016-2017

Research and Innovation Action

EU-SENSE

European Sensor System for CBRN Applications
(EU-SENSE)

Security Sensitivity Assessment

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 787031

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Publication type:	Report
Related WP number:	WP1
Which conference/journal, etc.	
Dissemination level: (Confidentiality)	Public
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Date:	29.10.2021

Objective

This form is related to the Security Sensitivity Assessment procedure which will assure that no sensitive information will be included in the publications and deliverables of the EU-SENSE project.

Security sensitive information means here all information in whatever form or mode of transmission that is classified by Council Decision on the security rules for protecting EU classified information (2011/292/EU) and all relevant national laws and regulations. The information can be already classified, or such that it should be classified.

In practice the following criteria is used:

- Information is already classified
- Information may describe shortcomings of existing safety, security or operating systems
- Information is such, that it might be misused.
- Information that can cause harm to
    - European Union
    - a Member State
    - society
    - industry and companies
    - third country
    - citizen or an individual person of a country.

Document Information

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