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Gas sensing in industry. A case study: Train hangar

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ABSTRACT

The detection and measurement of gas levels have become very important in both domestic and industrial fields. This is a result of the realization that certain gases are toxic and may have a harmful or even lethal effect on humans (and/or the environment), depending on exposure time or concentration. For this reason, gas sensors play a crucial role, especially in industries, where they help to prevent risks by detecting and measuring the presence of harmful gases in the workers' environment. There is a wide variety of sensors and techniques used to detect gases and determine their characteristics. The case study presented in this paper analyzes the presence of gases in a train hangar. Using a range of low-cost sensors, it is possible to measure the concentration of different gases over time and identify the moments where these concentrations are higher. In this study, it has been determined that these periods are usually related to moments when maintenance works are taking place in the hangar and their relationship with the measurements of a high-accuracy CO2 sensor. Detecting and predicting when these events take place allows to alert employees in case gas levels are considered dangerous for human health, or to take different actions to counteract this threat. An analysis of how to improve the energetic efficiency of the hangar is also carried out, estimating the losses caused by an inefficient ventilation system. Finally, some ideas are given to help improve the well-being of the workers, and also reduce energy costs.

1. Introduction and motivation

The field of gas sensing has experienced vast advances in recent decades. Sensors are now being used for multiple purposes, such as monitoring air quality in smart cities or in indoor spaces. Measuring air parameters in the natural environment or in industrial settings allows to detect the level of pollution and its effect on people. This is important as certain gases can be harmful to human health in both the short and long terms; it may even be fatal if the concentrations are very high. Frequent processes in industrial environments, such as combustion, are associated with the emission of different gases. Therefore, the ability to quantify, monitor, and even predict the levels of concentration of these substances in the air is very important and expensive.

Currently, there is a wide variety of sensors which operate differently and may be applied in a variety of scenarios depending on their features, therefore, it is necessary to choose the most suitable one for the circumstances in which the measurement is to be made.

After numerous studies, [1] it has been concluded that nanomaterials are highly suitable for use in sensing due to their diverse properties [2], concretely, the peculiar structure of graphene means that it has an ultra-sensitive response to the gas under study [3]. Metal oxide nanowires (MONWs) detect low levels of harmful gases such as NOx, COx, NH_3, CH_4, H_2S, SO_2, however, they are only able to effectively detect those gases when working at high temperatures. These sensors can be made up of metal oxides (MOS), such as ZnO [4], Fe_2O_3 [5], NiO [6], SnO_2 [7]. Those are the most common compounds, and they are often present in studies on oxygen-containing gases. Specifically, the sensors used in the case study (MQ2, MQ5, MQ7, MQ135) are based on the use of SnO_2 MOS for the measurement of combustible gases and fumes, $CH4, CO$, and NOx. Ionization sensors measure the characteristics of the sample once it has been ionized [8,9]. They work on the assumption that all gases under study will eventually be ionized when the appropriate voltage is applied. These detectors are used to measure NH_3, CO_2, N_2, O_2, He, etc. Non-dispersive infrared (NDIR) sensors are very popular, due to their high accuracy, stability, selectivity and good detection limit. This claim of sensors is used to detect gases based on their characteristic absorption of infrared radiation at specific wavelengths. NDIR sensors use an infrared source,

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a detector, and an optical filter to measure the concentration of a specific gas in the air. The technique is based on the fact that different gases have different absorption spectra in the infrared region of the electromagnetic spectrum. These sensors allow for the study of a particular gas without interference due to the presence of other gases. This type of sensor has been used for the measurement of CO_2 (MH-Z16) in the case study conducted as part of this research.

As mentioned above, gas level measurement is highly important nowadays and this is also reflected in the large body of studies in this field. Apart from the studies carried out in industrial environments, similar to the case study in question, air quality studies on gases concentration have also been carried out in a wide range of contexts.

Countless studies have been conducted for the measurement of indoor air quality. In the current context, this is of even greater importance, as poor indoor air quality indicates a propensity for the transmission of diseases such as Covid-19. This is the case of the analysis of indoor air quality in which data were collected from two hospitals and a primary care center in Portugal [10]. Temperature, relative humidity, CO_2 concentrations, bacteria, and fungi were measured and analyzed. Another study of interest is the one conducted in the gymnasium of a U.S. elementary school [11] where measurements were taken of temperature, CO_2, and relative humidity of indoor and outdoor air. A similar study is one in which indoor air temperature, relative humidity, and CO2 were monitored in different classrooms in a Polish university [12].

Moreover, case studies carried out in industrial environments have been analyzed, where harmful gases were present as a consequence of the activity being carried out there. These case studies are of great interest because they are similar to the research presented in this paper. The first of these is a study conducted at two workshops that logistically support offshore oil stations [13]. The case study pursued a monitoring and visualization approach to facilitate BigData decision-making for health and safety. Measurements of CO_2, relative humidity, and temperature were taken. Indoor air quality assessment in the refinery industry [14] is similar to the case study conducted as part of this research. The study examined chemical parameters, such as Respirable Suspended Particulate Matter (RSP), or the presence of different gases: CO, CO_2, TVOC, HCHO. Temperature, humidity, and air velocity had also been measured. The study took place in Port Klang, Malaysia, a major shipping hub. Furthermore, a project to monitor air quality was developed in a local palm oil mill factory located in Malaysia [15]. Palm oil mills are known to emit smoke and CO from the boiler, so it is important to measure the concentration of CO in the air. Finally, a study of indoor air quality was developed at a plastic factory in Garri, Sudan [16]. Nine parameters, such as CO, NO_2, CO_2, SO_2, TVOCs, PM2.5, RH, Noise, and light were detected.

The relationship between indoor air quality and the spread of Covid-19 is a matter that has also been studied, as it has great relevance in today's world. A study developed in Bangkok Metropolitan Area [17] has shown that parameters such as temperature or humidity are positively associated with Covid-19 cases, while gas concentrations, such as CO, NO_2, SO_2 or O_3, along with other parameters, such as PM10, PM2.5, and AQI, are negatively associated with Covid-19, so it is likely that the spread of Covid-19 is enhanced at facilities where these concentrations are especially high [18]. A similar research was developed in the City of Buenos Aires [19], concluding that exposure to air pollution was highly related with the risk of Covid-19 transmission and death.

The motivation behind this study is to measure and assess different parameters of interest within a train hangar. On the basis of the obtained results, it can be determined whether the facilities should be improved to increase energy efficiency. The severity of the damage caused by human-induced climate change depends not only on the magnitude of the change but also on the possibility of irreversibility. CO_2 emissions are therefore the greatest environmental concern and their capture is critical to reducing the effects of the greenhouse effect. Various agencies are urging emission reductions. The emission reduction targets set by the European Union for 2030 are to reduce emissions by 40% compared to 1990 and to improve energy efficiency by 27%. The Route established by the European Commission in Horizon 2050 aims to lower emissions to 80%, below 1990 levels and prevent the global temperature increase from exceeding 1.5 °C.

A series of modules have been distributed throughout the hangar to measure the fundamental parameters to be audited. The hangar is intended for the maintenance of commuter vehicles and locomotives. For this purpose, different certified sensors and communication modules have been used to quantify the levels of polluting gases (CO_2, NOx, etc.) as well as other parameters that are relevant for comfort, using the latest technologies available in sensorization and control.

This research article is organized as follows: Section 2 presents an overview of the details of the experiment, the methodology followed throughout the research and a review of different case studies which are similar to the one carried out as part of this research, whereas Section 3 details experimental results. The results of the case study are discussed and it is compared with other state-of-the-art studies in Section 4. Finally, in the last section, conclusions are drawn and future improvements are considered.

2. Details of the experiment

A train hangar is a place where pollution is frequent: many maintenance activities take place there. In addition to the pollution produced by trains, maintenance activities often result in a high concentration of harmful pollutants. Considering the hangar is a closed space, workers who work inside the hangar are highly exposed to dangerous gases such as CO. Following an extensive review of the state of the art in this sector, this study has been conducted to evaluate the risks associated with daily exposure to these substances. 16 multi-sensor devices have been deployed, which communicate by radio frequency protocol. They are capable of monitoring the hangar's condition. The system is able to give recommendations to activate forced ventilation of the area, and also alert of possible risks that workers may be exposed to. The final objective of the proposed solution is to improve the health conditions in these environments.

In this paper, a complete study of gas concentration levels has been carried out. Moreover, different environmental values have been monitored (temperature, pressure, and humidity) in a train hangar. For this purpose, a total of 16 sensor nodes have been distributed throughout the facility at different heights, and data have been collected continuously over a total of 23 days. CO_2 concentration has been analyzed in great detail, since it have been used as the main indicator of the quality of air, and the sensor used for measuring CO_2 has the highest accuracy among all the sensors used in this research. This is because the other sensors are low-cost, which has been useful when quantifying concentration variation, but they are not very reliable if precise gas concentration values are required. Moreover, the relationship between the concentration levels of the other gases has been examined to understand the extent to which the presence of one gas affects the others. Using this data it has been possible to observe that moments of high gas concentration always occurred during maintenance work inside the hangar. Thus, moments when maintenance work was being carried out in the hangar have been of interest to this study, as high gas concentration levels may strongly affect the health of workers.

Conclusions have also been inferred from the recorded temperature values and gas measurements, as one of the main objectives was also to conduct a study on energy efficiency. A series of solutions are suggested to improve the ventilation of the facility and reduce energy waste, including the possibility of directly implementing a system of gas extraction.

2.1. Hygiene, health and maximum exposure values

2.1.1. Pollutants

Many pollutants that are harmful to health may be found in the air: aerosols, dust, mists, smoke, etc. When determining the health risk factors associated with exposure to different pollutants, multiple factors may converge: the concentration of the pollutant, the time of exposure to this agent, the health condition of each individual, or the presence of several pollutants at the same time [20]. Let us look at the characteristics and the effects of some of the most common gases in daily life in more detail. Carbon dioxide is a colorless and odorless gas that is heavier than oxygen, which enables it to displace oxygen and cause the concentration of CO_2 to increase. Unlike some of the other gases described below, CO_2 plays a big role in creating the greenhouse effect. As human respiration generates CO_2, the concentration of CO_2 is often considered an indicator of air quality. Carbon monoxide is a colorless, odorless, and tasteless gas, somewhat less dense than air, so it diffuses rapidly. CO poisoning is rare, making it difficult to identify and diagnose. The major source of CO poisoning comes from automotive exhaust [21]. Nitrogen oxides, specifically N_2O, are widely used in the healthcare setting for their anesthetic effect and have been found to cause miscarriages in women who have had high and prolonged exposure to these compounds [22]. Methane is a component of natural gas, and although under normal conditions it is not harmful, in high concentrations it can reduce oxygen concentration and cause suffocation.

2.1.2. Exposure limits

To quantify human exposure to these gases, a series of variables have been defined to indicate whether the presence of these gases in a given room creates a risk, as shown in Table 1 below. Thus, the Ceiling Value (TLV-C) is the concentration that must not be exceeded at any time, ensuring that there is no risk of intoxication. In practice, if instantaneous monitoring is not feasible, it can be assessed by sampling every 15 min, except for substances that may cause immediate irritation during brief exposures. For the daily exposure limit, average values have been calculated from a total period of 8 h of exposure. These values are generally referred to as DE (Daily Exposure) and SE (Short Exposure), which may be expressed either in ppm or in densities (mg/m$\hat{3}$).

Since 1999 the National Institute for Safety and Hygiene at Work has been issuing a publication on occupational exposure limits for chemical agents. The National Commission for Safety and Health at Work has agreed to recommend that the exposure limits indicated in the INSHT guide entitled “Document on occupational exposure limits for chemical agents in Spain” be applied in workplaces and that their application be carried out according to the criteria established in that document. An updated document for 2021 is available: INSST (2021) Occupational Exposure Limits for Chemical Agents in Spain 2021, from which the following have been obtained, as shown in Table 2.

CO_2 is of special interest, because as previously mentioned, it is an important indicator of the quality of the air we breathe. Moreover, its levels indicate whether a room is well ventilated or not, so that we know if the environment is prone to virus transmission, as in the case of Covid-19. The occupational exposure limit value (LEP-VLA) of INSHT for daily exposures of 8 h is 5000 ppm with a limit value for short exposures of 15 min at 15,000 ppm. The UNE 100-011-91 standard as shown in Table 2 recommends a maximum concentration of 1000 ppm (parts per million) in indoor environments. Some agencies propose taking concentration measurements, suggesting that from a concentration of 800 ppm onwards, a review of the ventilation operation should be carried out.

Table 1
Exposure limits for different gases.

Gas	Formula	Daily Exposure		Short Exposure	
		ppm	*mg/m^3*	*ppm*	*mg/m^3*
Nitrogen monoxide	NO	2	2,5		
Nitrogen dioxide	NO_2	0,5	0,96	1	1,91
Sulfur dioxide	SO_2	0,5	1,32	1	2,64
Carbon monoxide	CO	20	23	100	117
Carbon dioxide	CO_2	5000	9150		
Ammonia	NH_3	20	14	50	36
Methane	CH_4	1000			
Chlorine	Cl			0,5	1,5
Chlorine dioxide	ClO_2	0,1	0,28	0,3	0,84
Lead	Pb		0,15		
Cyanides of:	Ca, H, K, Na		1		5
Sulfhidric acid	H_2S	5	7	10	14
Ozone (light duty)	O_3	0,1	0,2		

2.2. Data acquisition system

2.2.1. Sensing modules

To carry out the study, a system of 16 wireless sensor modules has been developed, which were placed at different points of the hangar, as shown in Fig. 1. It was decided to place them at different heights in order to measure the entire interior volume of the building. A receiver module, located in the offices on the side of the building, with access to the internet network, acts as a gateway for transmitting the data collected by each of the sensors to a visualization platform such as Thingsboard.

2.2.2. Architecture

Due to the characteristics of the hangar’s interior area, it has been decided to use a long-range IEEE 802.15.4 wireless communication standard (LoRa). The master–slave paradigm has been chosen, where the receiver plays the role of master and the transmitter modules are the slaves. The Fig. 2 shows the scheme of the architecture used in the project.

The transmitter modules, located at different points in the building, send data of different environmental parameters (temperature, humidity, pressure, air quality and various gases) to a concentrator device, which acts as an RF gateway. This gateway is responsible for managing the incoming information through a Python program. To ensure data persistence, a local database is located on the Raspberry Pi, and an external server with RAID 6 hard disks, which guarantees data preservation in the event of a catastrophic failure. In parallel, a connection to the Thingsboard client is used through an MQTT messaging protocol, based on a publish/subscribe model, where the device publishes messages to a specific topic.

2.2.3. Gas sensing transmitter modules

The sensor modules have been developed using modular designs (as a “shield”). In this way, they can be used in other researches and the PCB with the RF module can be used for both the transmitter modules and the receiver module (Radio Frequency Gateway). The following Fig. 3 shows a diagram with the electronic architecture of the device, showing 3 different PCBs that are connected together as a sandwich.

- The first PCB is the power shield. It has a connector for an external 5 V and 10 W power supply, with which the circuit is powered. An LDO voltage regulator is used to provide an output voltage of 3.3 V from an input voltage of 5 V. This regulator is needed to power electronic components such as the microcontroller and the BME680 sensor (both components are explained below).

Table 2
Air quality depending on CO_2 concentration.

Concentration	Air quality	Color
Below 350 ppm	High air quality	🟩
Between 350 and 500 ppm	Good air quality	🟨
Between 500 and 800 ppm	Moderate air quality	🟧
Between 800 and 1200 ppm	Low air quality	🟫
Above 1200 ppm	Low air quality	🟥
Above 5000 ppm	Very low air quality	⬛

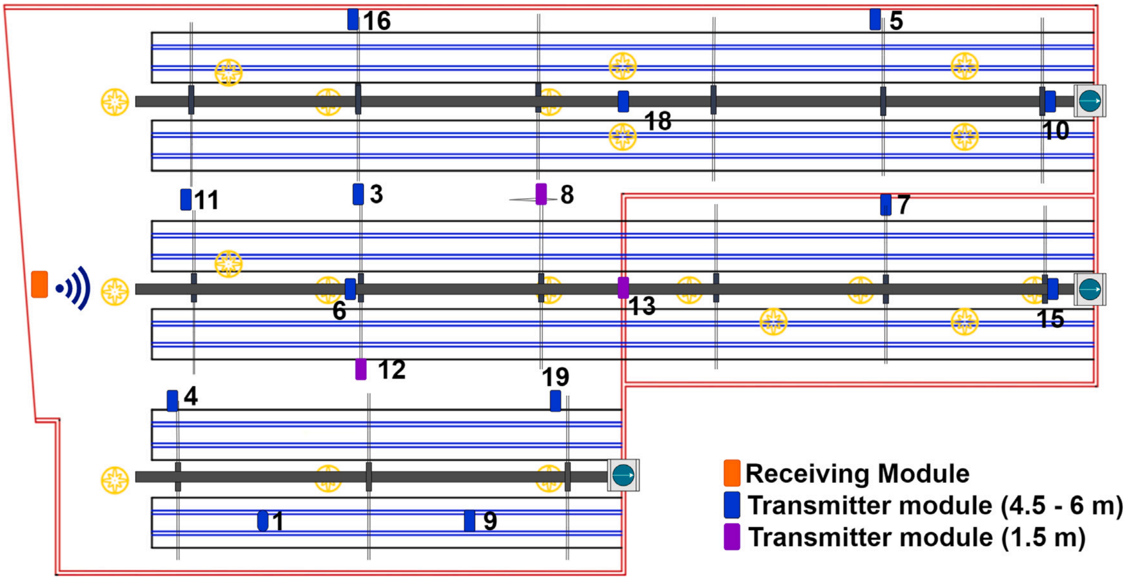


Fig. 1. Sensor distribution.

- The second PCB is the control and RF shield. The main component of this board is the CC1352R MCU, from the Texas Instruments manufacturer. This microcontroller is based on the 32-bit ARM Cortex-M4F architecture and incorporates a sub-1 GHz and 2.4 GHz multiprotocol RF module. The design incorporates a dual-band PCB antenna capable of operating at 868 MHz and 2.44 GHz. Finally, the FT230XQ-R integrated has been used as a "USB to UART" interface; and a micro USB connector, with which to transmit data via USB to external equipment. These last components are only assembled in the RF concentrator version.
- The third PCB is the gas sensor shield. This PCB has the necessary sensors to measure the parameters required in this research. The sensing module measures carbon monoxide CO (MQ7), carbon dioxide CO2 (MH-Z16), methane CH4 (MQ5), nitric oxide NOx (MQ135) and combustible gases and fumes (MQ2). It also integrates BME680, which measures temperature, humidity, pressure and air quality. The BME680 and MH-Z16 sensors transmit data to the microcontroller via serial communications (I2C and UART, respectively), while the MQ sensors have an analog output, which can be interpreted by the microcontroller's 12-bit ADC.

The performance of the gas meter module has been designed in such a way that the data, captured by the sensors and interpreted by the microcontroller, is sent wirelessly using the TI SimpleLink Sub-1GHz protocol on the public European frequency band of 868 MHz. The choice of this type of frequency allows the signal to be transmitted over long distances with greater wall penetration than a signal at higher frequencies. The gas measurement is carried out periodically every 3–5 min. For this, a rigorous method of data collection, verification and transmission is followed. The integrity of the data is thoroughly checked at each transmission, repeating the communication in case of inconsistency.

The transmitted data are received by an RF gateway, which is the device in charge of managing them.

2.2.4. Sensor calibration

In the case of CO_2, the MH-Z16 sensor is used, due to its main characteristics: high sensitivity and resolution, low power consumption, fast response, long life, etc. Additionally, the sensor is highly accurate and stable, which is important for long-term monitoring of CO_2 concentrations. It operates by emitting infrared radiation at a specific wavelength that is absorbed by CO_2 molecules, causing a reduction in the intensity of the radiation. The sensor then detects the remaining radiation and uses this information to determine the concentration of CO_2 in the air. Each sensor is factory calibrated, but for this calibration to be reliable it is necessary to keep the sensor on and reset it periodically, to prevent it from calibrating automatically in a contaminated environment since this behavior cannot be changed. The restart is completed in less than 3 seconds, which prevents the sensor from needing to warm up again to provide reliable results. It only requires 3 min of activity to provide valid readings. The calibration is valid for the first 6 months, so we can guarantee that during this test only valid data have been obtained.

Other gases (CO, CH4, NOx...) are measured with low cost sensors of the MQ family. To ensure maximum lifetime, these devices have been subjected to a 24-h carbonization period without interruption. Once this period is over, the sensors are ready for use.

2.2.5. RF gateway

An RF gateway is a device used to connect wireless communications networks to an Ethernet or WiFi network, allowing wireless devices to access a longer-range network and the internet. It acts as an intermediary between the wireless devices and the network to which they are connected, receiving information from the wireless devices and transmitting it across the network for processing and storage. The gateway is composed of an RF concentrator and a Raspberry Pi-based processing module, as shown in Fig. 4:

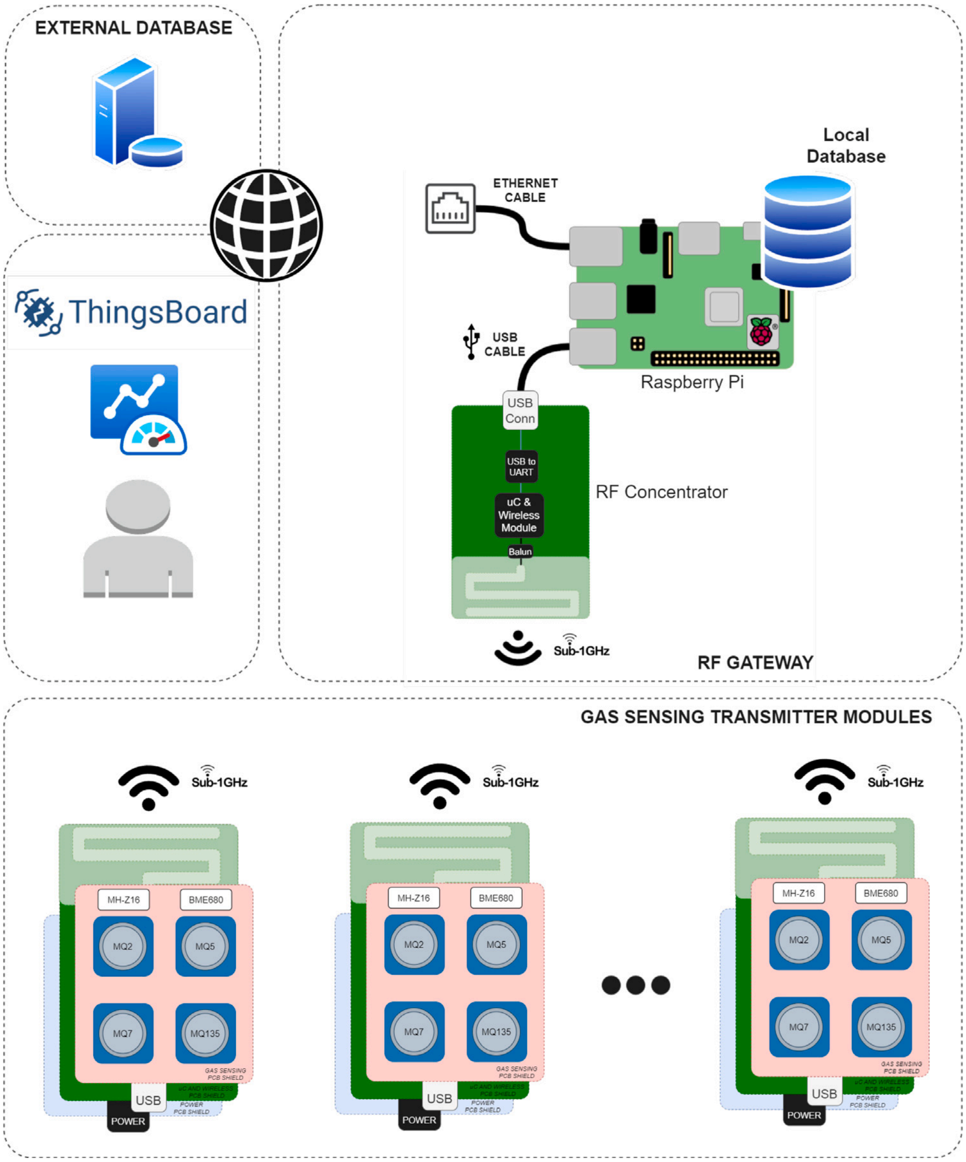


Fig. 2. Architecture.

- The RF concentrator is the device responsible for receiving signals from various wireless devices and concentrating them into a single signal for transmission over a network. For this purpose, the RF and control shield, described above, are used, with all electronic components soldered together. The data received through the wireless module of the CC1352R microcontroller is redirected to the Raspberry Pi via USB serial communication.
- The processing module makes use of a Raspberry Pi, which is a complete computer with a processor, memory, storage and connectivity, but in a very compact and inexpensive form factor. It is responsible for managing the data coming from the RF concentrator (via USB cable) and transmitting it to the network via an Ethernet cable or a WiFi connection.

The code developed for data management consists of two main threads: one for reading and one for sending. Fig. 5 shows a schematic of the data processing.

The reading thread is in charge of receiving serial data, although it is developed to receive data from other sources. These data are analyzed and, in case they are consistent, they are stored in a FIFO queue. A second thread takes the data from the queue, in order of arrival, and transmits it to two destinations: an external data server, which robustly guarantees data stability; and the IoT Thingsboard platform, where it is collected, processed and visualized.

In order to be able to use the system in cases where we have train hangars in remote regions with less connectivity. There are different commercial solutions based on radio frequency and satellite connectivity that offer global coverage all over the world. Two examples are Lacuna and EchoStar. Both use the LoRaWAN protocol with a frequency of 868 Mhz in the case of Lacuna and 2.1 Ghz in the case of EchoStar, which allows the collected information to be sent with minimal consumption.

2.2.6. Dashboard

The Thingsboard environment offers real-time monitoring that improves decision-making by providing graphs that the user can adapt, depending on the periods being analyzed. It also offers basic statistical data such as averages and threshold values. This type of data visualization contributes to faster decision-making, which in turn reduces operating costs by improving business logic, eliminating unnecessary costs, and optimizing others. The following diagrams show the CO_2 data collected by six different nodes during the same period (Fig. 6).

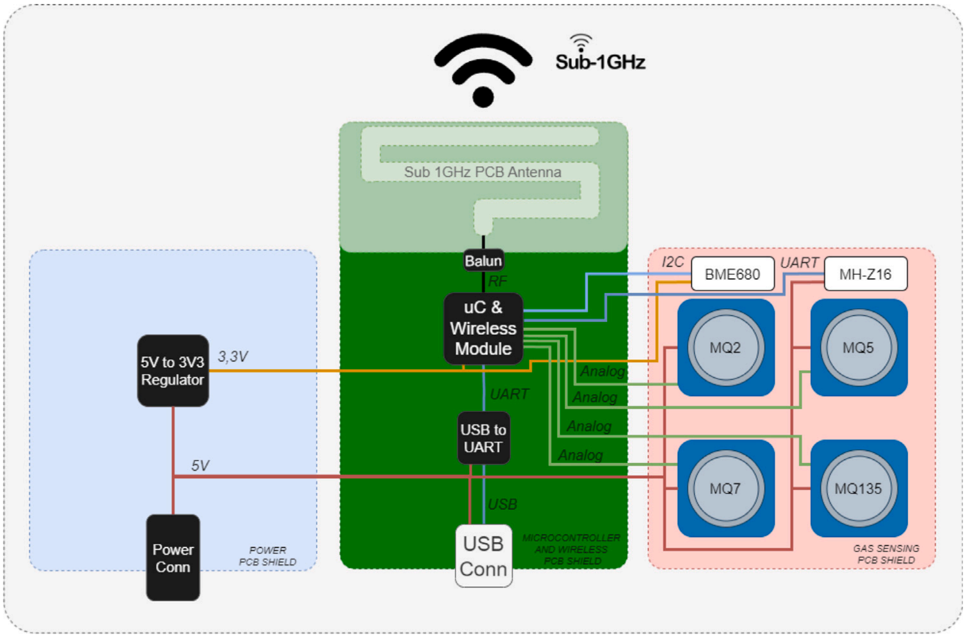


Fig. 3. Architecture hardware.

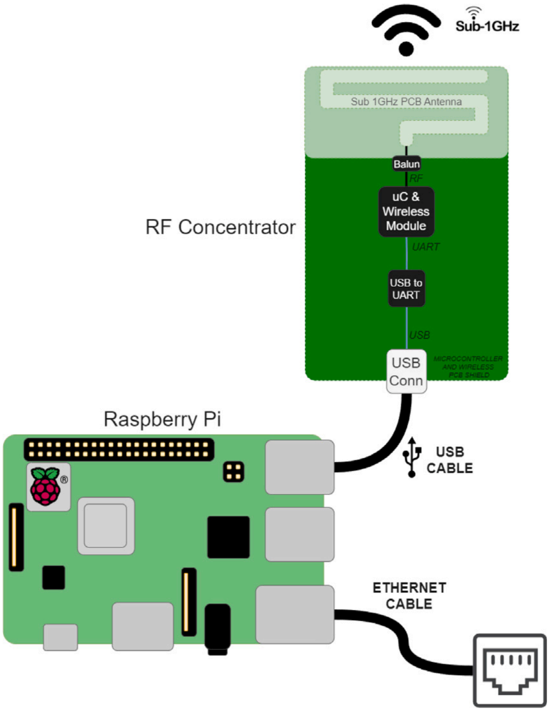


Fig. 4. Data treatment scheme.

3. Experimental results

In total, data has been collected for a total of 23 days. The dates on which the facility has been monitored range from 10/12/2019 to 23/12/2019 and from 2/01/2020 to 12/01/2020. The data collected by each of the modules were sent to the receiver module every 30 seconds, which in turn sent the data to the database. A total of 900,000 data have been collected during the period that the hangar has been monitored.

3.1. CO_2

The maximum value reached for CO_2 is 5279 ppm. Concerning the air quality intervals seen previously, this value shows that the air in the hangar is very poor, at this level it is very harmful to humans.

3.1.1. Maximum values per node for CO_2

The following Fig. 7 shows the maximum values reached by each node. All of them, except node 3, exceed the limit of 1000 ppm established in the NTP 549 standard. Many of the nodes have maximums close to, or even exceeding, the value of 5000 ppm, which shows very poor air quality.

3.1.2. Average values per node for CO_2

The absolute average for all measurements of CO_2 is 449,39 ppm. The following graph Fig. 8 shows the total average CO_2 per node. Although train maintenance work is not always performed, it is significant that many averages exceed 600 ppm. For CO_2 values above 600 ppm, the NTP 549 standard states "the most sensitive individuals already manifest complaints and discomfort".

3.1.3. Values in maintenance per node for CO_2

The absolute average in maintenance for CO_2 is 682,97 ppm. According to the collected data, the CO_2 averages in ppm have been calculated for the moments after train maintenance, Fig. 9. These moments are the ones we are most interested in because they discard the values of the moments when the hangar is without any activity.

The averages per node in the hours after maintenance reveal a low air quality, as mentioned above, according to NTP 549, the most sensitive individuals suffer from CO_2 concentrations above 600 ppm.

3.1.4. Daily average of CO_2 *in maintenance*

The table below, (Fig. 10) shows the daily average of CO_2 when there is maintenance work. We observe that the average CO_2 is very high on most days. On many days average air quality was low or moderate. In some cases, the average air quality was very low. The number of days that exceed 600 ppm on average is very high. As mentioned earlier, the NTP 459 standard indicates that above 600 ppm the most sensitive individuals are impacted. Similarly, prolonged exposure to these levels can cause long-term respiratory problems.

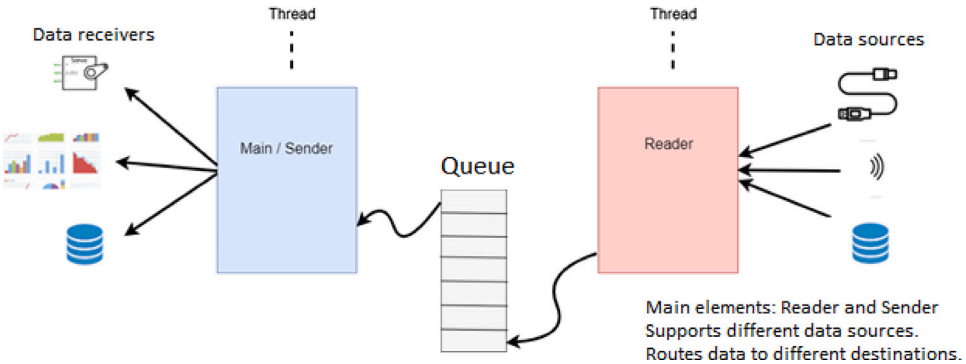


Fig. 5. Data treatment scheme.

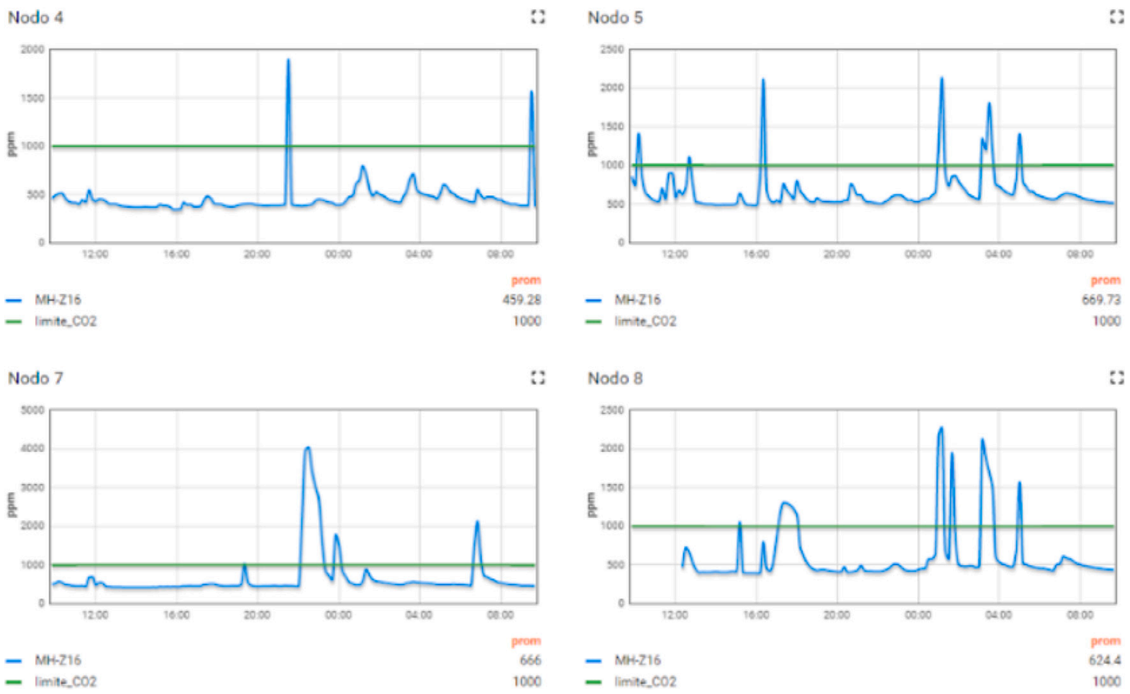


Fig. 6. Thingsboard panel measuring CO_2.

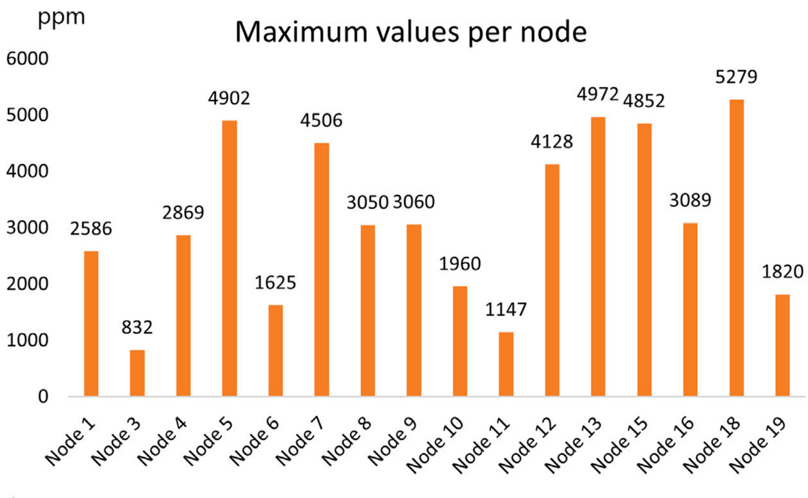


Fig. 7. Maximum values per node for CO_2.

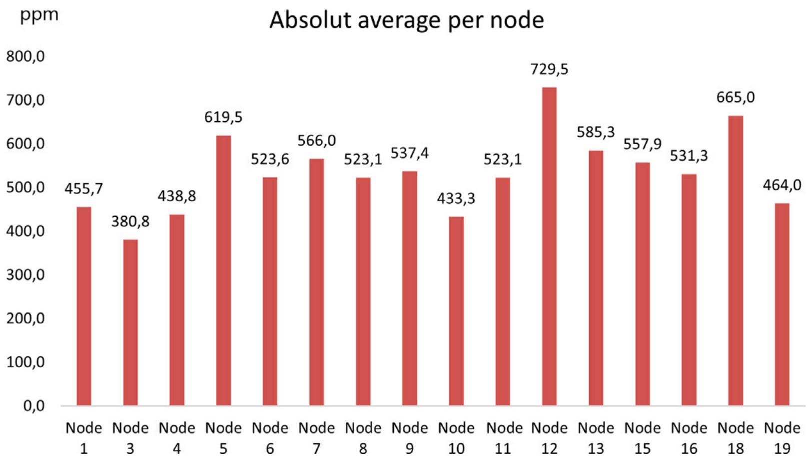


Fig. 8. Absolute average per node for CO_2.

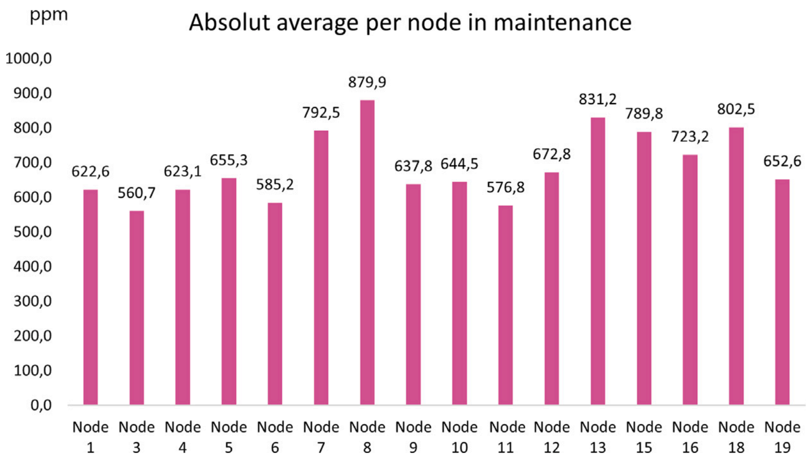
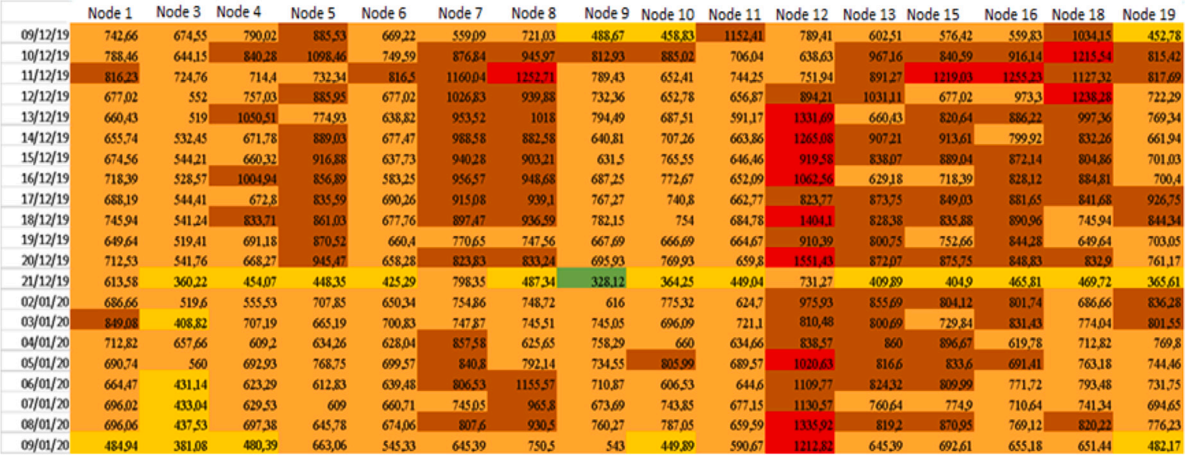


Fig. 9. Maintenance average per node for CO_2.



	Node 1	Node 3	Node 4	Node 5	Node 6	Node 7	Node 8	Node 9	Node 10	Node 11	Node 12	Node 13	Node 15	Node 16	Node 18	Node 19
09/12/19	742,66	674,55	790,02	885,53	669,22	559,09	721,03	488,67	458,83	1152,41	789,41	602,51	576,42	559,83	1034,15	452,78
10/12/19	788,46	644,15	840,28	1098,46	749,59	876,84	945,97	812,93	885,02	706,04	638,63	967,16	840,59	916,14	1215,54	815,42
11/12/19	816,23	724,76	714,4	732,34	816,5	1160,04	1252,71	789,43	652,41	744,25	751,94	891,27	1219,03	1255,23	1127,32	817,69
12/12/19	677,02	552	757,03	885,95	677,02	1026,83	939,88	732,36	652,78	656,87	894,21	1031,11	677,02	973,3	1238,28	722,29
13/12/19	660,43	519	1050,51	774,93	638,82	953,52	1018	794,49	687,51	591,17	1331,69	660,43	820,64	886,22	997,36	769,34
14/12/19	655,74	532,45	671,78	889,03	677,47	988,58	882,58	640,81	707,26	663,86	1265,08	907,21	913,61	799,92	832,26	661,94
15/12/19	674,56	544,21	660,32	916,88	637,73	940,28	903,21	631,5	765,55	646,46	919,58	838,07	889,04	872,14	804,86	701,03
16/12/19	718,39	528,57	1004,94	856,89	583,25	956,57	948,68	687,25	772,67	652,09	1062,56	629,18	718,39	828,12	884,81	700,4
17/12/19	688,19	544,41	672,8	835,59	690,26	915,08	939,1	767,27	740,8	662,77	823,77	873,75	849,03	881,65	841,68	926,75
18/12/19	745,94	541,24	833,71	861,03	677,76	897,47	936,59	782,15	754	684,78	1404,1	828,38	835,88	890,96	745,94	844,34
19/12/19	649,64	519,41	691,18	870,52	660,4	770,65	747,56	667,69	666,69	664,67	910,39	800,75	752,66	844,28	649,64	703,05
20/12/19	712,53	541,76	668,27	945,47	658,28	823,83	833,24	695,93	769,93	659,8	1551,43	872,07	875,75	848,83	832,9	761,17
21/12/19	613,58	360,22	454,07	448,35	425,29	798,35	487,34	328,12	364,25	449,04	731,27	409,89	404,9	465,81	469,72	365,61
02/01/20	686,66	519,6	555,53	707,85	650,34	754,86	748,72	616	775,32	624,7	975,93	855,69	804,12	801,74	686,66	836,28
03/01/20	849,08	408,82	707,19	665,19	700,83	747,87	745,51	745,05	696,09	721,1	810,48	800,69	729,84	831,43	774,04	801,55
04/01/20	712,82	657,66	609,2	634,26	628,04	857,58	625,65	758,29	660	634,66	838,57	860	896,67	619,78	712,82	769,8
05/01/20	690,74	560	692,93	768,75	699,57	840,8	792,14	734,55	805,99	689,57	1020,63	816,6	833,6	691,41	763,18	744,46
06/01/20	664,47	431,14	623,29	612,83	639,48	806,53	1155,57	710,87	606,53	644,6	1109,77	824,32	809,99	771,72	793,48	731,75
07/01/20	696,02	433,04	629,53	609	660,71	745,05	965,8	673,69	743,85	677,15	1130,57	760,64	774,9	710,64	741,34	694,65
08/01/20	696,06	437,53	697,38	645,78	674,06	807,6	930,5	760,27	787,05	659,59	1335,92	819,2	870,95	769,12	820,22	776,23
09/01/20	484,94	381,08	480,39	663,06	545,33	645,39	750,5	543	449,89	590,67	1212,82	645,39	692,61	655,18	651,44	482,17

Fig. 10. Daily average of CO_2 in maintenance (in ppm).

3.2. Other pollutants

The presence of others gases that are harmful to health is also analyzed, most of them come from the exhaust of a diesel cycle internal combustion engine. Despite the complex amalgam of compounds produced because of combustion, this study presents the behavior of the most relevant ones: carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (mostly NO_2), and low molecular weight organic compounds, usually aromatic compounds such as toluene or naphthalene or short-chain hydrocarbons such as methane, ethane, propane or butane

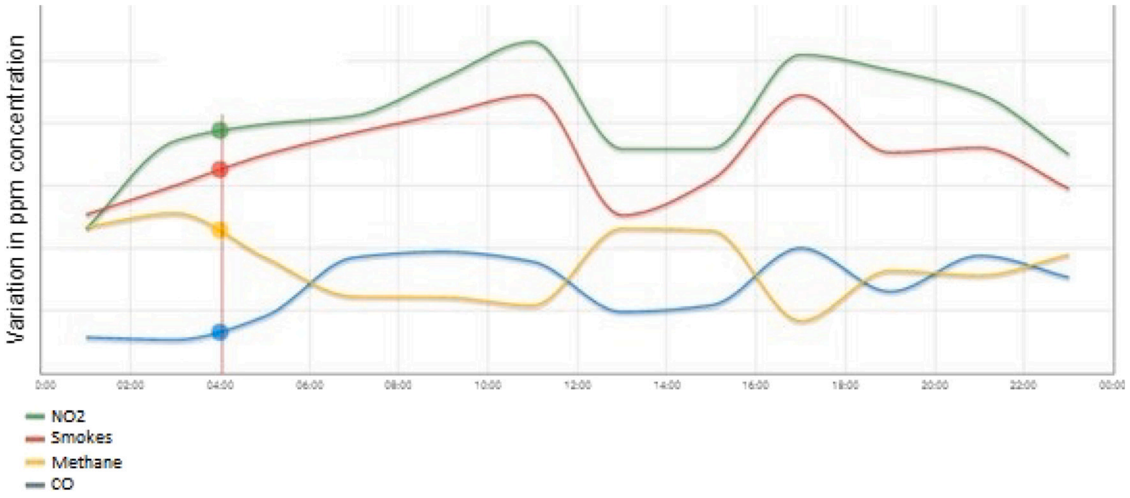


Fig. 11. Gas dynamics throughout an entire day.

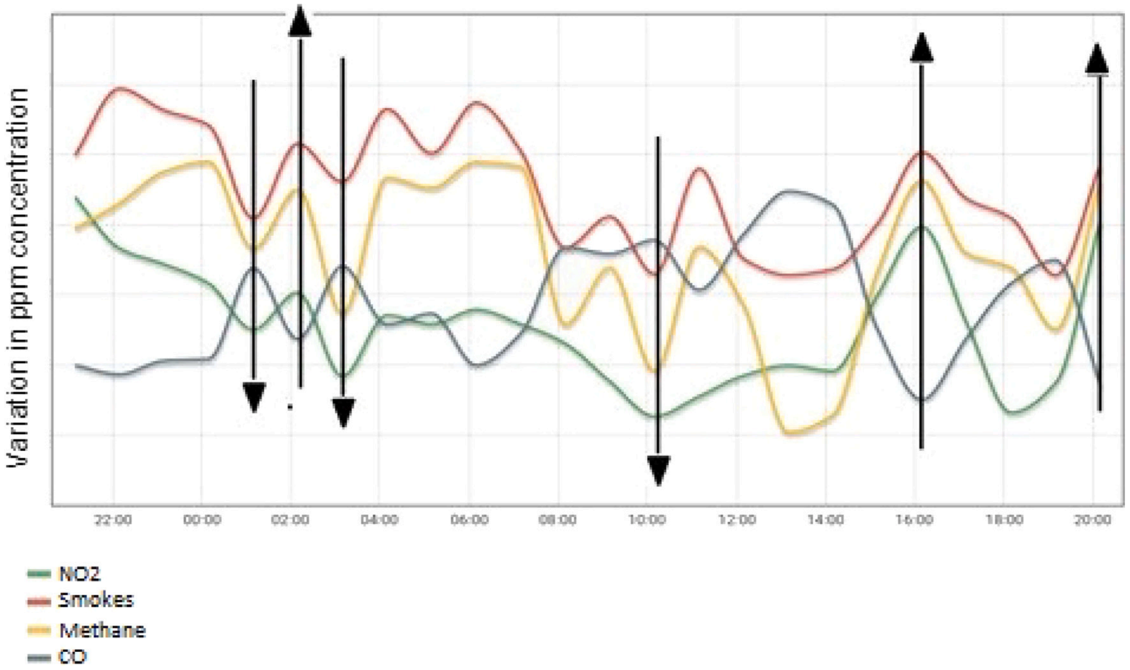


Fig. 12. Gas dynamics analysis Node 5.

(LPG). Previously we have seen the exposure limits associated with carbon monoxide, CO, or nitrogen dioxide, NO_2. However, for polycyclic aromatic hydrocarbons, no threshold level can be determined since all indoor exposures are considered health-relevant.

- Explanation of gas dynamics
  The different densities of the gases in the study explain the dynamics observed in the compared measurements, highlighting that some gases take the place of others, thus, denser gases displace heavier ones and vice versa, and these dynamics are observable as a function of the distance to the ground of the sensor. Table 3 shows the densities of each of the gases:
  Case 1: 09-12-2019 (Fig. 11)
  Case 2: 17/12/19 - 18/12/19 (Fig. 12)
  In cases 1 and 2 it can be seen how carbon monoxide, which is lighter than the rest of the gases, occupies the space causing the rest of the readings to decrease when it is present. Therefore, this reading has been taken by a sensor located at a high altitude, otherwise, the dynamic would be just the opposite.
  Case 3: 09/12/19 (Fig. 13)
  In case studies 3 and 4 what we try to show is the correlation of the measurements with the time instant in which they are displayed. Here we can see how the appearance of the CO_2 peaks took place earlier than the appearance of the other peaks in the rest of the sensors. This is because the MH-Z16 sensor uses the non-dispersive infrared principle, and this allows an almost instantaneous response time (less than 10 seconds from the appearance of the gas in the vicinity of the sensor) as opposed to the MQ family of sensors in which the gas causes an electrolytic reaction inside the sensor.
  Case 4: 13/12/19 (Fig. 14)
- BME Analysis Temperature, Humidity and Pressure.
  First, temperature for Node 10, located on the roof, was analyzed. Fig. 15 the maximum temperature measured was 21.97 °C, while

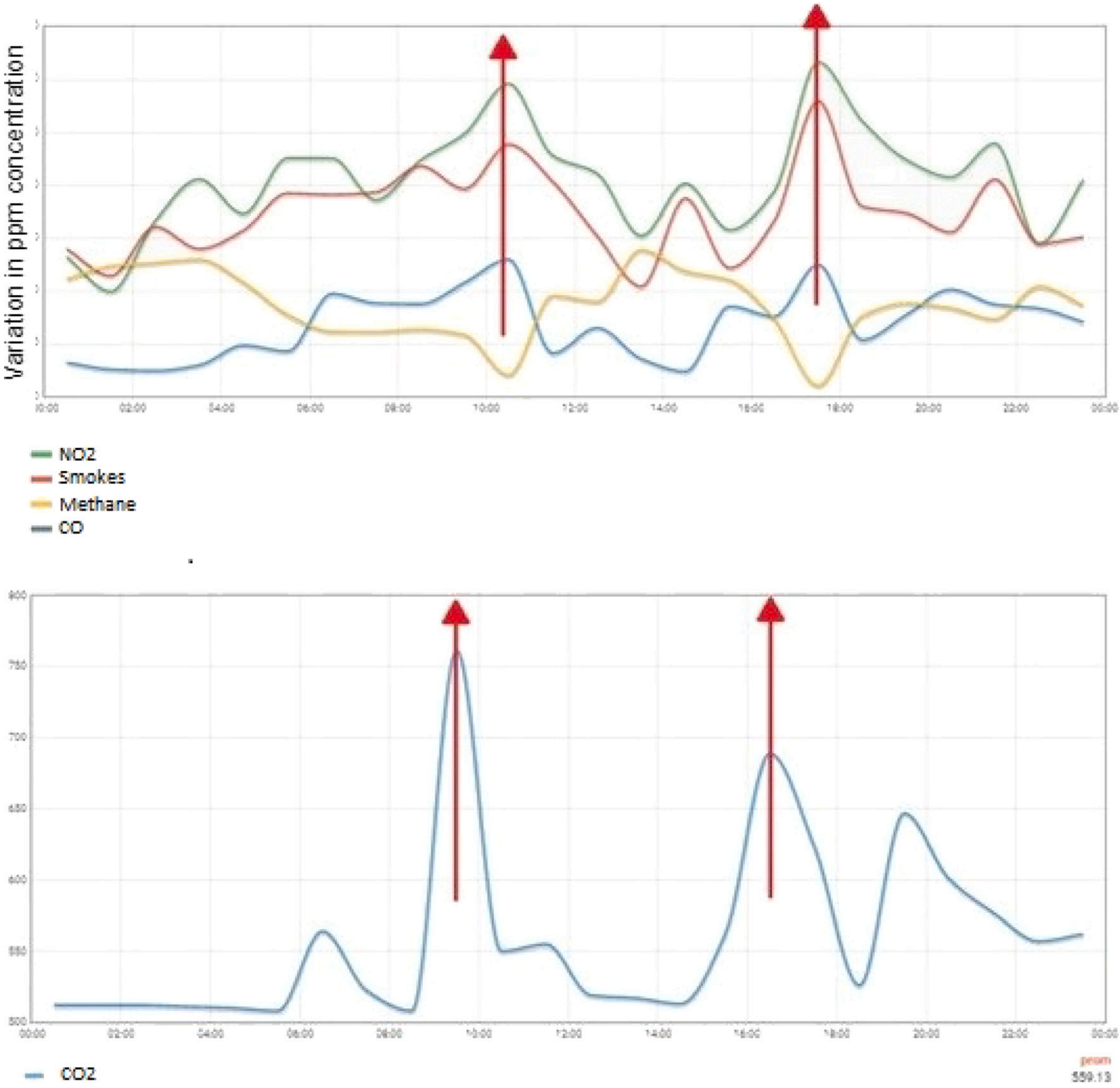


Fig. 13. Comparison between CO_2 concentration (below) and concentration from the rest of the gases (above).

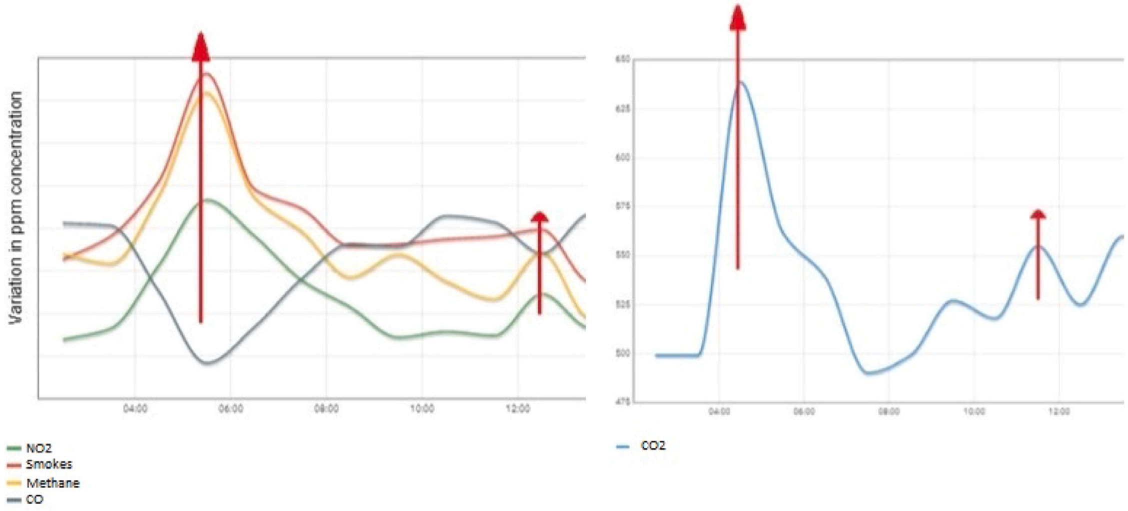


Fig. 14. New comparison between CO_2' concentrations and other gases Node 5.

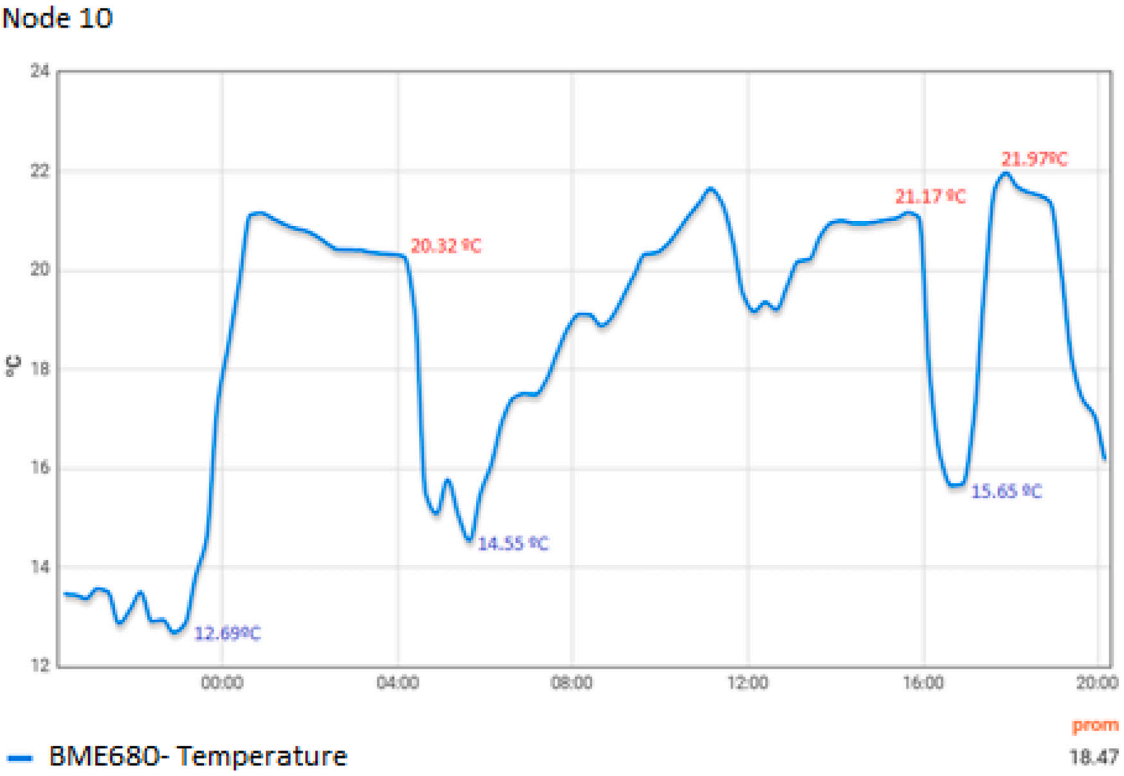


Fig. 15. Temperature during 24 h for Node 10.

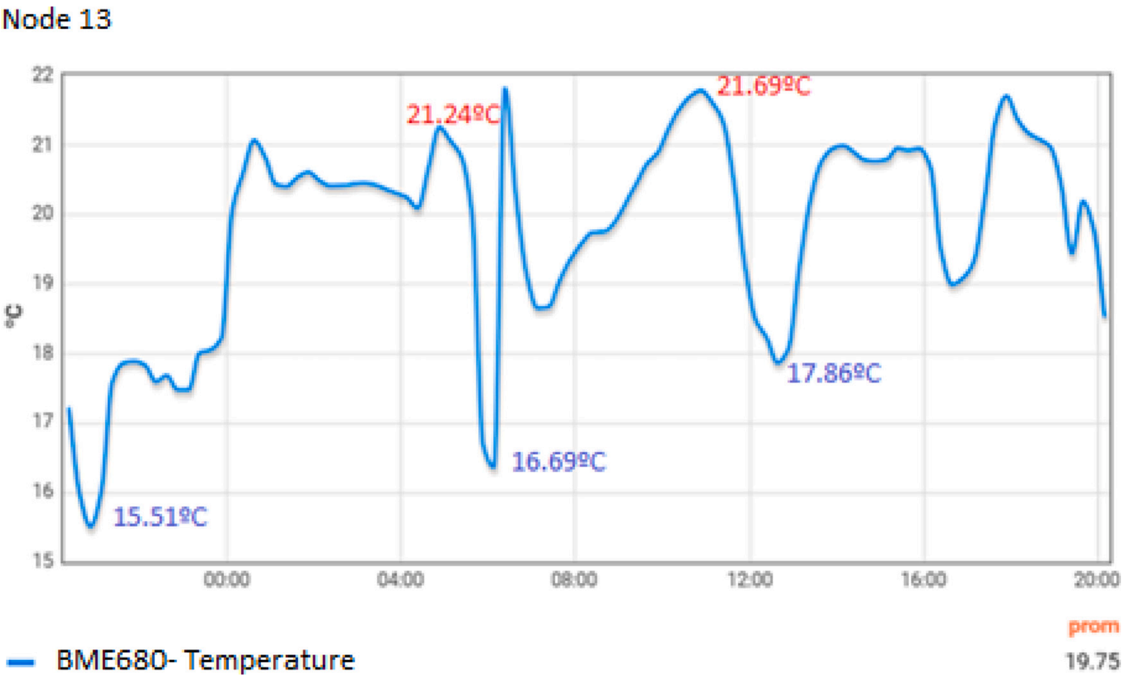


Fig. 16. Temperature during 24 h for Node 13.

the minimum was 12.69 °C and the average temperature was 18.47 °C.

Now temperature for Node 13, located on the floor, was analyzed. Fig. 16 the maximum temperature measured was 21.69 °C, while the minimum was 15.51 °C and the average temperature was 19.75 °C.

As it can be seen in the graphs, the measured temperature has large variations within the same day. These are due to the opening of the gates to bring the trains into the facilities. As it is a manual opening system, the operators do not close the gates instantly when all the carriages are inside, but on many occasions, they forget to close them until some time has passed. This results in a very inefficient heating system, reducing the temperature by up to 5 °C in only 30 min. Therefore, a system of automatic opening and closing of the gates is recommended to increase the efficiency of the heating system. This would result in savings in

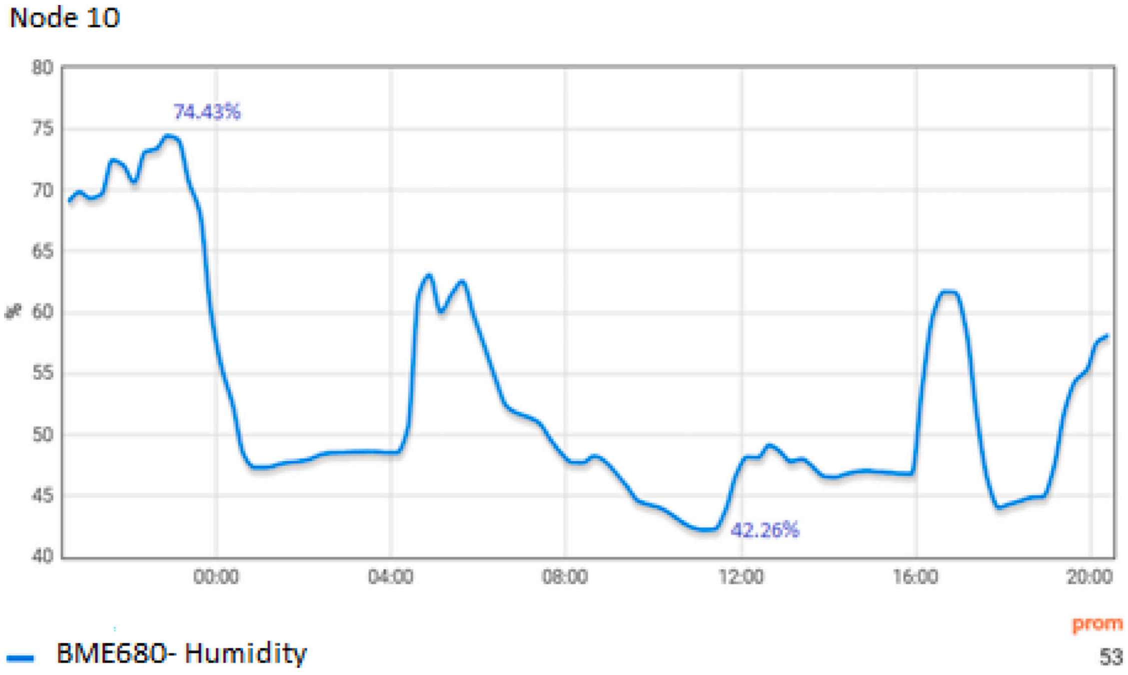


Fig. 17. Humidity for Node 10.

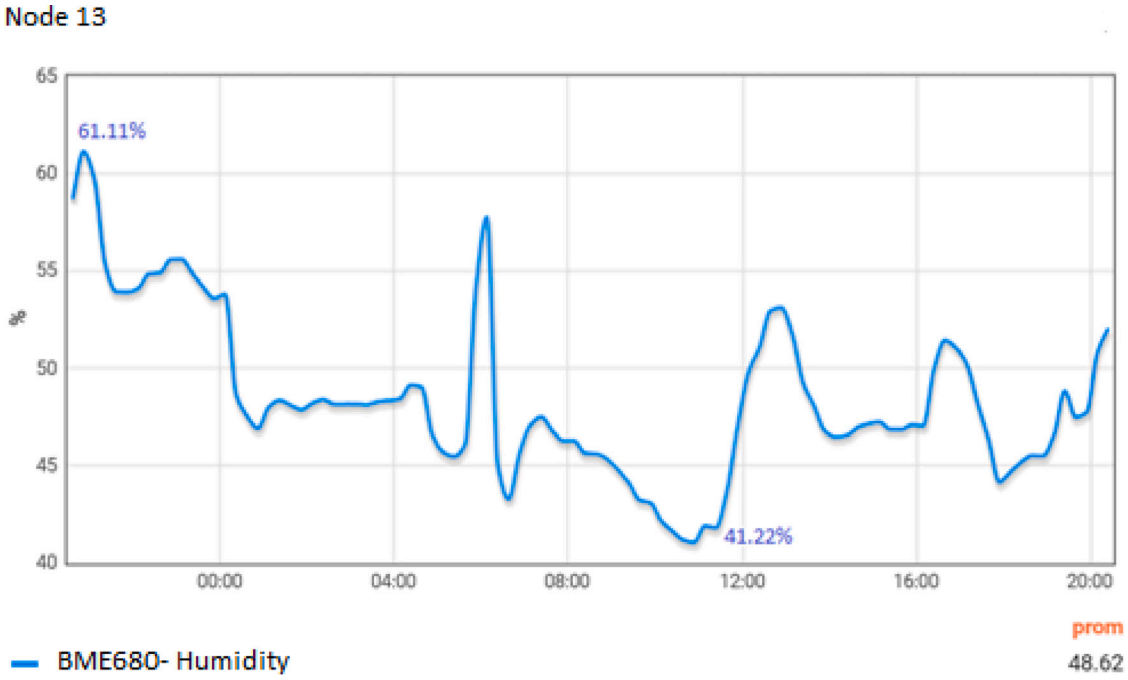


Fig. 18. Humidity for Node 13.

heating costs. What is also interesting about the incredible drop in temperature during gate opening periods is the energy cost to increase it again. If we consider that the enclosure has 16,000 m3̂, that the air weighs 1.205 (kg/m)3̂ and that 1000 calories (1.2 W) are needed to increase by 1 °C the temperature of 1 kg of air, 23 KW would be needed to increase the air at the facility by 1 °C. Every time the doors remain open, all the energy is lost in the form of heat produced by the boiler and accumulated inside the building, plus the energy dissipated by the heating system at that moment. This dynamic is complex to model and costly to simulate, but according to the data obtained from this study, which shows how the surface temperature of the floors dropped, the habit of keeping the doors open may be responsible for 80% of the current energy consumed on heating.

- Humidity
  The following graph shows the values of humidity inside the hangar during an entire day. The first one is for a sensor located at the roof (Node 10, Fig. 17), while the second one corresponds to a sensor located on the floor (Node 13, Fig. 18).
  As it can be seen in the humidity graphs, these are related to the temperature graphs and show that when the doors are opened, air enters from outside, and the humidity inside the facilities increases. Figs. 19, 20 provide a comparison of the temperature vs. humidity graphs for the same period, which shows:

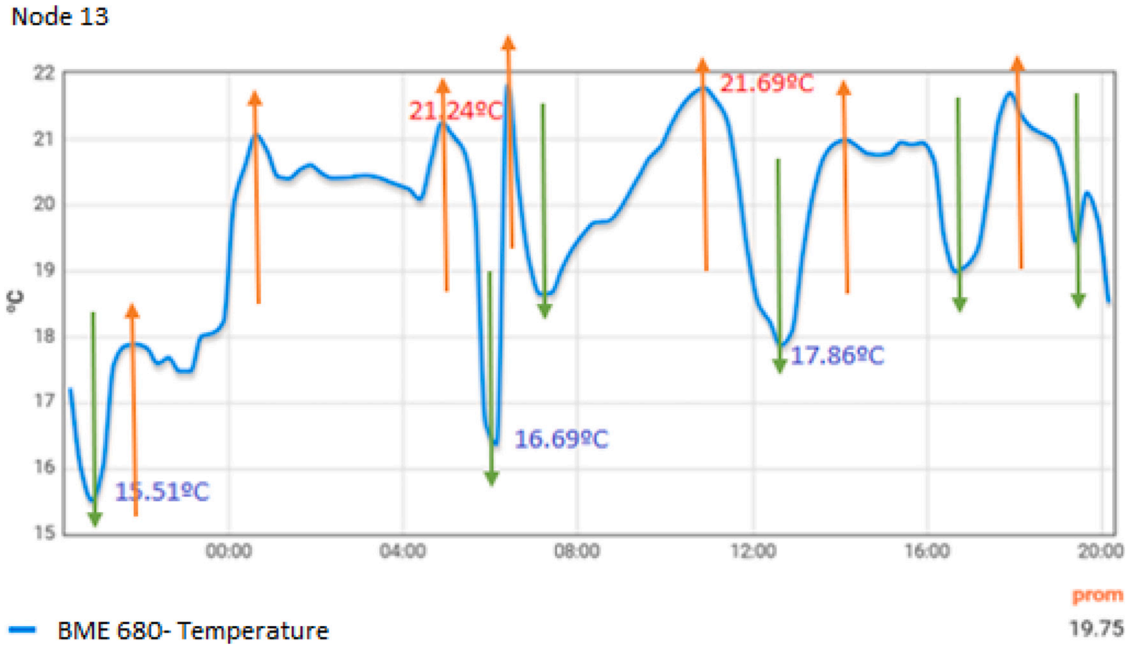


Fig. 19. Temperature for Node 13.

Table 3
Density of different gases.

Gas	Density	Sensor
Air	1.225 kg/m^3	–
CO_2	1.976 kg/m^3	MH-16
CO	1.140 kg/m^3	MQ7
NO_2	1.450 kg/m^3	MQ135
Methane*	1.282 kg/m^3	MQ5
Smokes	Depends on the temperature	MQ2

- Pressure
  In terms of pressure, there is no relevant data to comment on (Figs. 21, 22). The pressure at ground level and roof level does not vary at all.

4. Discussion

Other studies had already considered the measurement of air quality and gas monitoring, such as CO_2 analysis of indoor air quality by collecting and analyzing data from two hospitals [10], measurements of CO_2, relative humidity, and temperature at offshore oil stations [13] or indoor air quality assessment in the refinery industry [14]. However, what differentiates our study is that a network of monitoring devices had been deployed to analyze the conditions in the hangar in real-time. Moreover, it has been possible to analyze what implications each of the monitored parameters had for health and hygiene in industrial environments, considering gases individually and when combined.

The measurements that appear in this document show that during maintenance periods, in which the diesel engines of the locomotive wagons are in operation, the CO_2 measurements are in values are at the limit (either almost reaching the limit or surpassing it). There have been multiple readings which reached five times the admissible threshold for significant periods of time. Given the limited operational capacity of the carbon monoxide, organic gases, and nitrogen oxide sensors, it has been possible to determine from the dynamic of the masses of gases that alter the measurements of neighboring sensors, that the quantities of these toxic gases are significant enough to require a more extensive study, which would require sensors of moderate cost and high precision. Given the strict admissible limit for the CO molecule and nitrogen oxides, it is evident that these limits are widely exceeded, but it is impossible to determine the exact amount. Also, due to their toxicity, a second study with a larger budget for sensing is strongly recommended. Despite being of special relevance to the combustion product of diesel cycle engines, the analysis of PM 25 particles and smaller has not been contemplated in this study because it was not included in the initial requirements elicitation by the client. Given that these particles are hazardous to health, as they are deposited at the bottom of the lungs and can even pass into the blood, it would be crucial for a future investigation to focus on air quality and the healthiness of maintenance facilities.

Given the obtained temperature values, it is possible to calculate the amount of energy and the cost of ventilating the facilities either by using forced ventilation to eliminate environmental pollution or by the loss of hot air masses when the hangar doors are opened to introduce machinery. For these calculations, an estimated air volume of 16,000 m^3 and a temperature difference of 5 degrees on average have been used. The cost of increasing the ambient temperature of the facility by 5 °C after the gates had been opened amounted to 27 KWh. If we consider that on average the gates are opened 6 times, and the efficiency of the boiler, pipes, and installations is, optimistically, at 60%, then 11.78 KWh/kg of diesel is consumed and the price of diesel in Spain on 09/01/2023 is at 1.77€. Thus, the total cost amounts to 40.36€ per day. For a period of normal heating operation of 6 months a year (at this location the operation always lasts at least 8 months) annual spending on diesel oil heating caused by the process of opening and closing the gates would amount to 7183€.

The energy dissipated through the walls, roof, and pipes that do not have appropriate insulation should be added into the calculation, however it has not been measured in this study, as the efficiency of the heating system has only been determined by measuring data on how many of the generated calories were kept as heat within the facilities and how many were lost in the process. However, despite the complexity of modeling and simulating such a system, we estimate that 8 out of the 10 kilowatts used by the HVAC system were lost due to the inefficient use of the facility's dampers and ventilation system.

5. Conclusions and future improvements

The main objective of this report was to assess air quality in a train hangar, measuring different parameters such as CO_2, fumes, $CH4$, CO,

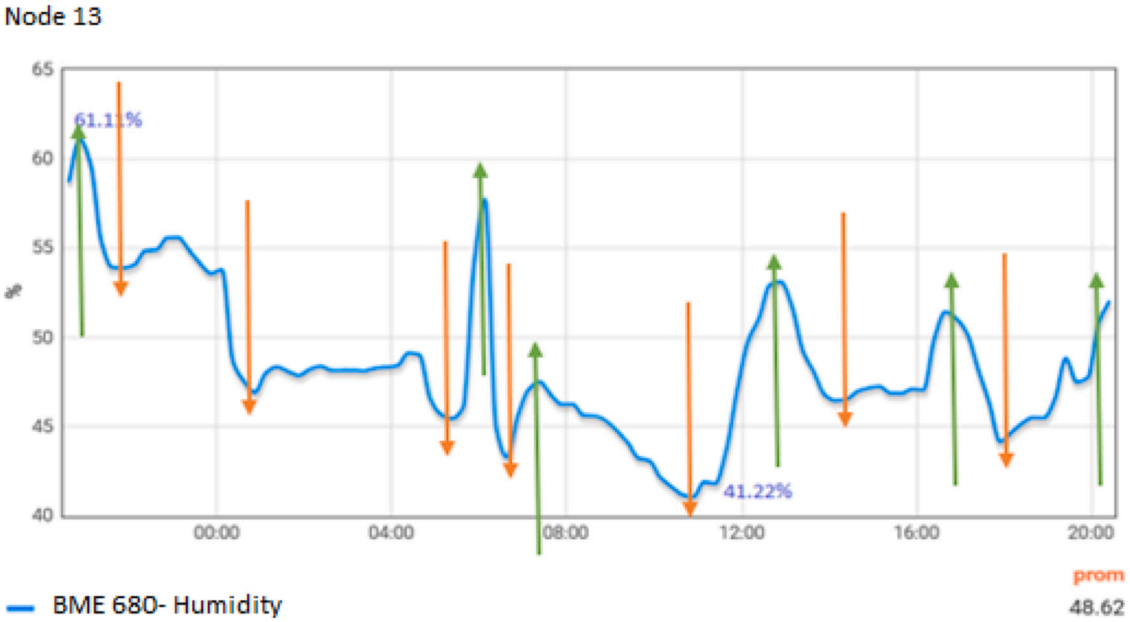


Fig. 20. Humidity for Node 13.

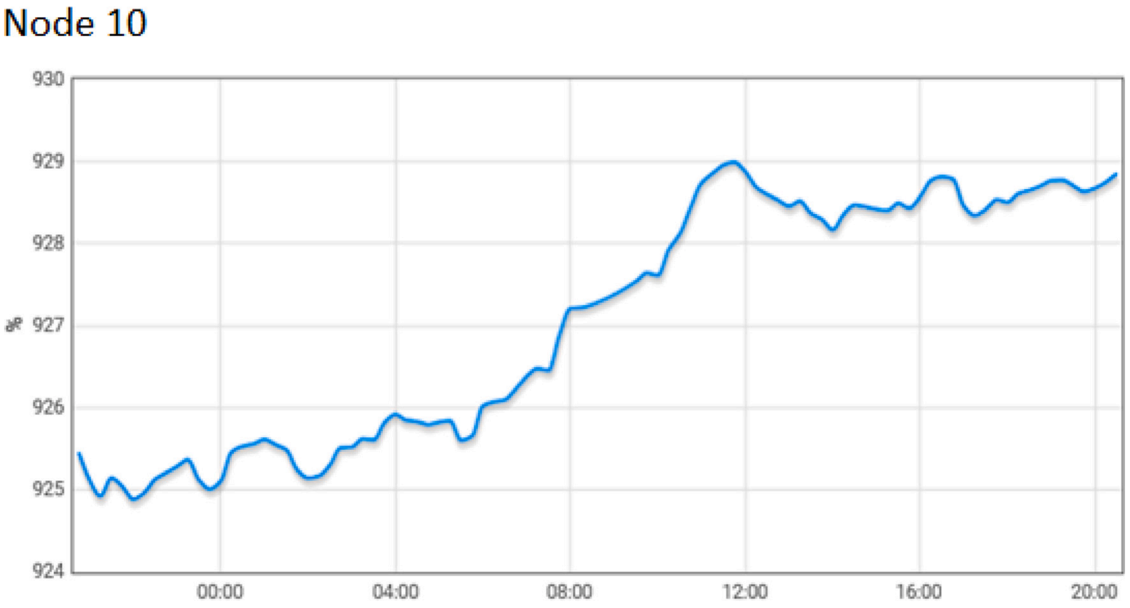


Fig. 21. Pressure for Node 10.

and NOx concentration, pressure, temperature, or humidity. The system designed for this purpose was successfully implemented, providing numerous measurements that were later analyzed to find out whether the conditions inside the hangar were acceptable according to different legislation.

In terms of occupational health and environmental impact, given the results obtained in this report, it is suggested to implement a gas extraction system that would maintain the energy efficiency of the facilities and even improve it by eliminating the need for ventilation. At the same time, health risks associated with exposure to diesel combustion products would be eliminated, which would significantly improve the health of all the workers near or inside the hangars. The objective of the study is the use of low-cost sensors for air quality measurement and hazardous gas detection. Normally these sensors tend to have a very high price that makes their use inaccessible for an adequate measurement in industrial environments. Thanks to this study, a window is opened to the use of low-cost sensors for air quality measurement and hazardous gas detection.

Also, a CO_2 capture system that would reduce the environmental footprint to values close to zero in maintenance work could be implemented. As it has been described, CO_2 is the main pollutant in the air, so air quality would improve significantly just with the implementation of this system. The environmental impact of the hangar could be studied by measuring and comparing environmental values in the vicinity of the hangar with those from areas that are not exposed to this source of pollution, so it can be determined whether the hangar is polluting the surrounding areas.

In conclusion, the study presented in this paper highlights the importance of gas sensors in detecting and measuring the presence of harmful gases in the workplace. The use of low-cost sensors provides a cost-effective solution for continuous monitoring, allowing for the detection of peak periods of gas concentration. The analysis of gas

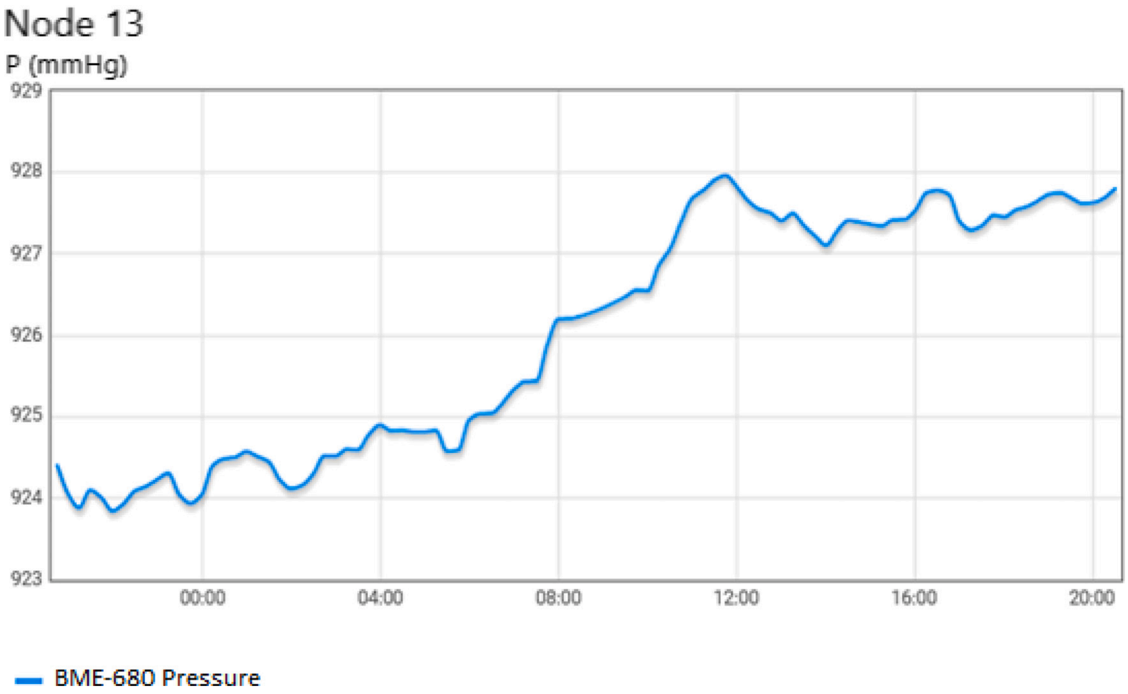


Fig. 22. Pressure for Node 13.

levels in a train hangar, combined with the study of the ventilation system, has provided valuable information for the optimization of the energy efficiency of the workplace, reducing both energy costs and the impact on the environment. Furthermore, suggestions are given to improve the well-being of workers, ultimately creating a safer and healthier work environment. This study demonstrates the potential of gas sensors in improving safety, efficiency, and worker comfort in industrial environments.

Finally, a further study could be carried out to measure the extent of damage to the health of workers, by doing surveys and medically examining all the employees that are working in this hangar, determining whether they have experienced any health problems (respiratory difficulties, dizziness, etc.) in the workspace, and learn about their perception of this matter.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Fernando De la Prieta Pintado reports financial support was provided by Spain Ministry of Science and Innovation.

Data availability

Data will be made available on request.

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Its main line of research is the application of artificial intelligence in different fields: education, biometric identification, artificial vision and data analysis. In terms of the publication and dissemination of results, the most noteworthy is the set of 24 publications in international journals, 13 of which stand out with an impact factor, according to the Journal Citation Reports (JCR) index (10 Q1, 3 Q2). Likewise, in more than 50 publications in books and international congresses, some of them included in the CORE, SCI, etc. rankings. He has participated in multiple European (5), national (15) and regional (8) research projects and more than 20 collaboration contracts with private and public sector companies, being PI in several of them.

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Dr. De la Prieta is equally well experienced in research and teaching, as evident in his curriculum. Over the past years, he has followed a clearly defined line of research, focusing on the integration of multi-agent organizations, machine learning and advanced architectures in different fields. He applied the results in both his doctoral thesis (for which he obtained an international PhD mention and an extraordinary PhD award) and in the projects he has been involved in. He has more than 50 publications in international journals, many of which have a JCR impact factor on the Web of Science database. His H index in Google Scholar is 27. Furthermore, he has published more than 100 articles in books and in the proceedings of prestigious international conferences, around thirty of these publications have been published in conferences indexed according to the CORE ranking. He has worked on more than 90 research projects (16 of them were international and in several he has been the principal investigator). In addition, he has participated in more than 30 research contracts (Art. 83), in some of them as the principal investigator. As a result of his work, around 40 intellectual properties have been registered. He has done several stays abroad (pre- and post-doctoral) in Portugal, Japan and South Korea. He has also taken an active part in the organization of international conferences, some of them included in the CORE ranking: IEEEGLOBECOM (core B), ICCBR (Core B), CEDI, PAAMS (core C), ACM-SAC (core B), IEEEFUSION (core C), and others.