Low-Cost LoRa-Based IoT Edge Device for Indoor Air Quality Management in Schools

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Abstract. Indoor Air Quality (IAQ) is an essential requirement for improving building sustainability. In fact, indoor pollution creates serious problems for human health and occupants' well-being. Considering that Europeans spend on average 90% of their time inside buildings, IAQ plays a decisive role in human health, especially for the most vulnerable groups such as the elderly and children. Concerning children and youth, due to the presence for long periods of time in school classrooms, they tend to be more susceptible to developing chronic diseases such as asthma, allergies, and respiratory problems or make these problems more increased. In these circumstances, to prevent the occurrence of these specific illnesses, it is essential to improve the school environment, namely, classroom ′ indoor air quality. This research aims to specify both the design and development processes of a LoRa-based IoT Edge device for classroom IAQ monitoring, by using low-cost commercial off-the-shelf components, capable of measuring relevant IAQ parameters specifically selected for a specific case-study analysis, namely the following: carbon dioxide (CO_2), particle matter, and volatile organic compounds (VOC). At last, the prototype is delivered and assessed under controlled conditions. It is also worth highlighting that the prototype's overall cost is approximately 150€.

Keywords: IAQ · IoT · Edge computing · LoRa

1 Introduction

Humankind spends most of their time in enclosed places [1], especially people living in urban areas, who are estimated to spend about 80–90% of their time in households, offices, school buildings, shopping centers, malls, and supermarkets [2]. This is particularly sharp for the school-age population (children and adolescents), who spend an extremely high percentage of their time in these areas [1]. Therefore, well-ventilated spaces providing fresh air are fundamental to improve indoor environmental quality, which includes not only Indoor Air

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Quality (IAQ) but also other physical and psychological variables of people's life indoor, just like thermal comfort, lighting, acoustics, etc. [3]. Given the importance of the theme, IAQ has been put on the environmental agenda in the last few years [4], with a particular focus on school buildings [3]. In fact, new specific legislation for all European countries has been providing appropriate recommendations to tackle indoor air quality problems within school environments [3], emphasizing both the need of reinforcing ventilation rates through natural or mechanical schemes to dilute pollutants and to reduce the number of airborne contaminants and particles generated indoors. The list of atmospheric pollutants to be taken into consideration for IAQ assessment and management includes gases (carbon monoxide, radon, volatile organic compounds, etc.), particulates, and microbial contaminants (mold, bacteria). These pollutants are associated with harmful health impacts, which can even be fatal [3] and cause significant socioeconomic effects by reducing the productivity levels in schools and work environment [4]. In school buildings' classrooms it is possible to find various types of gases and particle matter (PM) that negatively impact pupils' health and attention, such as carbon dioxide, radon, particle matter (PM1, PM2.5, and PM10), volatile organic compounds (VOCs), among others. As for PM, it is proved that the finer the particles, the more serious the effects on human health [5]. Despite its regular presence in indoor environments, the amount of these contaminant substances can change throughout the year. In fact, in colder months, during the winter season, the pollutant emission is generally higher, due to the increase in human activities and the warming of the environment. Likewise, high relative humidity rates associated with the low air renovation during winter blocks aerosol elimination or removal. In the summer season due to the positive effect of natural ventilation, the indoor air pollutant concentration is lower. However, cooking on stoves (frying mainly), burning garbage, smoking indoors, and vehicle traffic are, for both seasons, the main sources of particle matter emissions [4]. Additionally, other factors contribute to IAQ degradation, such as the proximity to pollutant factories and combustion activities on the building surroundings, among others [6]. Furniture and decoration accessories can be responsible for IAQ deterioration since wooden materials emit formaldehyde, and both new paints and flexible plastics are associated with respiratory problems and allergies, especially prevalent in children [7].

IAQ monitoring and control are therefore mandatory for school classrooms since it is of the utmost importance to offer a healthy, safe, comfortable, and productive environment for the entire academic community [1]. In fact, high concentrations of air pollutants in school classrooms, aggravated by inadequate ventilation conditions, is generally associated with poor student performance [8], and higher rates of school absenteeism [1]. The lack of ventilation tends to aggravate problems related to high formaldehyde concentrations due to the high density of furniture [3–9], incrementing therefore the risk of asthma and reducing academic performance in school-age children.

Thereby, school classroom IAQ monitoring is one of the top priorities for a Smart Campus since it contributes, both to improve students' learning ability, and to increase teachers' productivity [10]. Thus, IAQ assessment by performing a continuous classroom ′ monitoring is a path to create healthy and comfortable schools, and to reduce energy consumption. [2]. At the same time, it will help to increase students' school performance while preventing possible negative impacts on their health [1].

In this article, a prototype of an integrated IAQ monitoring system is presented, more specifically, its design and overall architecture. In this prototype, an IoT Edge device is designed to assess indoor air temperature and relative humidity in a school classroom, as well as several IAQ parameters, such as CO_2, VOC, and PM, which were specifically selected for school IAQ assessment.

The collected data can also be used to infer the classroom occupancy, cf. [11,12], which can contribute to increasing its energy efficiency. For instance, the detection of an unoccupied school classroom with a heating system in operation may lead to an important energy saving.

This document is organized as follows: Sect. 2 introduces several related studies regarding IAQ in schools; Sect. 3 introduces the overall system architecture; Sect. 4 is dedicated to the design and detailed implementation of the IoT Edge Device; Sect. 5 presents the preliminary results; and finally, in Sect. 6 conclusions are undertaken and a final discussion is put forward.

2 Related Works

In [9], authors developed a study to assess IAQ in daycare centers due to the high vulnerability of children exposed to indoor air pollution and contamination. Daycare centers are public spaces, where you children spend part of their day while waiting for their parents. In this study, special attention was paid to particulate material, which is one of the most dangerous pollutants by causing very serious respiratory diseases in children, such as asthma. The objectives of the study were to assess, firstly, the indoor air concentrations in particulate material (PM1, PM2.5, PM10, and PMtotal) in different indoor environments, such as classrooms and canteen, for three different daycare centers on weekdays and weekends. External measurements of PM10 were also undertaken to obtain an I/O (Indoor/Outdoor) ratio. The results obtained showed that PM concentrations were particularly higher in the assessed classrooms, especially in the class of finer particles, reaching a maximum of $145\,\mathrm{mg/m^3}$ for PM1.0 and $158\,\mathrm{mg/m^3}$ for PM2.5. Both values are above the limits recommended by the World Health Organization (WHO), which allows concluding that room' ventilation with outdoor air affected indoor air quality, thus increasing PM accumulation. Therefore, it was concluded that daycare centers should increase air renovation rate after rooms' occupation, and must prevent air filtering to improve IAQ.

A study developed by Fraga et al. presented in [13], aims to analyze a possible correlation between IAQ and allergic and respiratory pathologies in students attending public schools in Porto, Portugal. The investigation carried out an in-situ assessment to evaluate relative humidity, CO_2, and VOC in a set of nine secondary schools. To complement in situ measurements, a representative sample of 1607 students were invited to answer a survey concerning demographic, social, and behavioral issues. This investigation applied the International Study of Asthma and Allergie in Childhood (ISAAC) questionnaire to assess respiratory symptoms. The attained results allowed concluding that for CO_2 concentration above 2100 ppm, students showed symptoms of cough, phlegm and wheezing, during exercise, and had a cough at night. Additionally, in the schools with higher VOC levels, the prevalence of asthma is higher, along with symptoms of wheezing and nocturnal cough.

In [14], authors present a system for indoor air monitoring and quality control in school building offices. To validate the system, four eight-hour tests in three distinct rooms were carried out under different ventilation conditions. The monitoring system allowed assessing CO_2, CO, relative humidity, and indoor air temperature. The authors concluded that the impact of air insufflation on indoor air quality is higher than the impact of air extraction.

3 IAQ in the Classroom

In Subsect. 3.1, the selected IAQ parameters to be assessed will be shortly described, as well as their implications regarding human health, including mitigation actions that must be undertaken when the regulated limits are exceeded. In Subsect. 3.2, the general system architecture will be explained and detailed.

3.1 IAQ Parameter Selection

By considering the related studies synthesized in Sect. 2, all focused on the relation between indoor air quality and allergic and respiratory pathologies in school classrooms, three parameters will be selected for assessment:

- **CO_2:** causes respiratory problems, eye irritation, flu and allergic rhinitis [15];
- **VOC:** affects the nervous system, causes headaches, liver problems and lack of memory [16];
- **PM2.5/PM10:** responsible breathing problems, such as asthma and bronchitis [17].

All selected parameters have negative effects on human health. To control its impact, there are regulatory limits that help to manage its indoor air concentration. For carbon dioxide, the legal limit is 1250 ppm [18]. When this value is exceeded, natural (or mechanical) ventilation actions must be performed to increase the air change rate in the classroom. The limit for VOC indoor air concentration is $600\,\mu g/m^3$ [18]. When this limit is exceeded, the room air change rate must be increased to improve air renovation. This can be easily achieved through natural ventilation actions, such as windows opening, which can be seen as the most basic natural ventilation method offering a very simple and low-cost solution to providing ventilation. Windows opening can provide background ventilation allowing to adapt the ventilation rate when required. Finally, the PM2.5 legal limit is $25\,\mu g/m^3$, which, when exceeded, means that the room must be cleaned and sanitized.

3.2 Conceptual Architecture

Figure 1 illustrates the conceptual architecture used for integrated IAQ management in a school building. Each classroom is equipped with an IoT edge device that collects several IAQ parameters. The acquired data is then transmitted periodically using LoRaWAN communications, that can be available at a building or city level. LoRaWAN is a MAC protocol used for low power and long-range wide area networks that runs on top of the LoRa Modulation [19]. A LoRaWAN server is used to enable effective and transparent communication between the LoRaWAN network, the analytics engine, and the application server, simplifying the integration on the client-side.

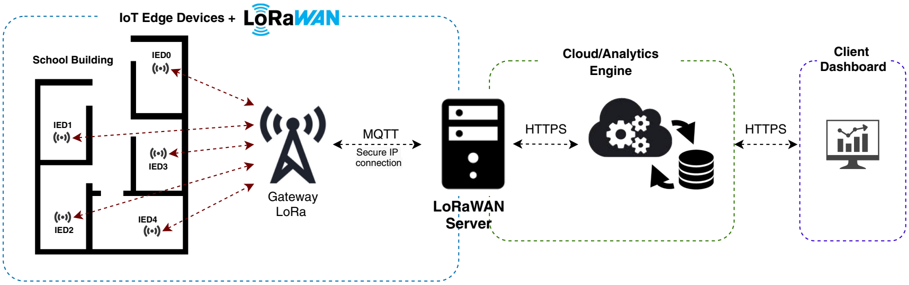

Fig. 1. Conceptual architecture with the core elements identified.

LoRaWAN protocol uses end-to-end security communications that rely on AES cryptographic algorithms. These algorithms have been widely adopted for securing constrained networks and devices [22–24]. For this, LoRaWAN uses three 128 bits AES security keys. Each LoRaWAN device is distinguished by a unique 128 bit AES Application Key (AppKey) and a globally unique device identifier (DevEUI), both used during the device authentication stage. After a device joins the LoRaWAN network, an Application Session Key (AppSKey) and a Network Session Key (NwkSKey) are generated. The AppSKey is kept private and the NwkSKey is shared with the network. Both keys are only used during the current session.

Additionally, the system includes a web-based app with a rich data visualization dashboard generated with the Grafana framework. Grafana is open-source software that provides a powerful interface for exploring time series data with native integration with several database types, turning it the standard for the visualization and analysis of this type of data. More details about the architecture in use can be found in [20,21].

4 IoT Edge Device

Figure 2 depicts the block diagram of the IoT edge device, where it is possible to visualize its three main blocks: 1) sensing, 2) processing, and 3) communications. The sensing block is composed of three digital interfaced sensors specified based on the selection previously introduced in Sect. 3.1 to measure the following parameters: relative humidity, temperature, CO_2, TVOC, and PM2.5/PM10. Note that each sensor is capable of measuring more than one parameter. Processing is guaranteed by an ESP32 microcontroller that includes, although not used, built-in Wi-Fi and Bluetooth connectivity, as well as several interface modules such as I2C, UART, PWM, ADC, DAC, among others. Communications block is guaranteed by a LoRa RFM95W modem, that can be configured to operate in the 868/915 MHz bands. With this radio module, it is possible to configure the device to operate as a client or even as a LoRa gateway. We included an additional RGB Led for user interface purposes.

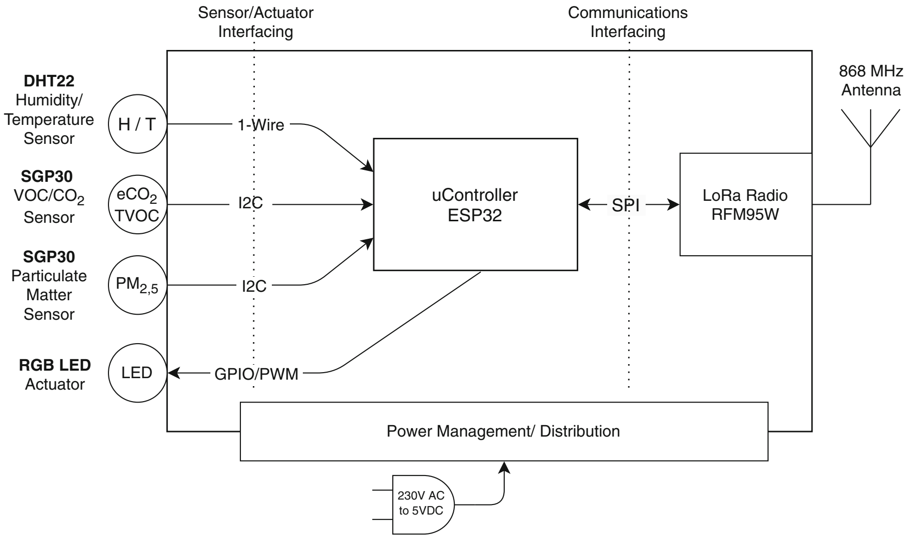

Fig. 2. IoT Edge device block diagram.

4.1 Hardware Development

Since educational institutions may have dozens of classrooms and offices, the cost is a critical factor, and a core requirement in the hardware design is to be low-cost and based on commercial off-the-shelf components. The sensor market is very competitive, with multiple manufacturers presenting low-cost solutions at the cost of reduced accuracy, making it often difficult for designers and engineers to choose the components that best meet the specific application requirements.

For the development of this device, the choice of the sensors was mainly focused on the cost-benefit regarding the component price versus its accuracy.

The DHT22 sensor was used to measure the relative humidity and temperature of indoor air. The DHT22 is a low-cost sensor that has an error of ±0.5 °C for temperature and ±2% for relative humidity, which suggests that the sensor has a high degree of accuracy. It can work with a voltage of 3.3 V to 6 V, thus communicating with the microcontroller through a 1-wire interface [25].

The SGP30 is a metal-oxide (MOX) gas sensor developed by Sensirion for Indoor Air Quality applications that features multiple sensing elements in one chip. It is equipped with an I2C interface and is capable of detecting a wide variety of volatile organic compounds (VOCs). However, the sensor returns the value of the Total VOC (TVOC), and the carbon dioxide equivalent (eCO_2), an indirect measure, that although not highly accurate, after calibration turns out to be a very reliable estimate that allows to effectively infer the CO_2 trend on a budget. The SGP30 can be used with 3.3 V or 5 V [26].

The SPS30 is an optical PM developed by Sensirion for the measurement of particle matter (PM). This sensor has a lower limit detection size of 0.3 µm and allows the measurement of the mass of particles up to sizes PM1.0, PM2.5, PM4 and PM10, and the number of particles up to sizes PM0.5, PM1.0, PM2.5, PM4 and PM10. In the previous notation, the lower number represents the maximum size in µm measured or counted, respectively. The sensor can communicate via I2C or UART and can operate using either 3.3 V or 5 V TTL levels [27].

The sensors previously introduced are wired to the ESP32 through I2C protocol, cf. Fig. 2, except for DHT22, which connects through a digital 1-wire interface. In terms of power, only the SPS30 needs to be powered with 5 V.

4.2 Firmware Development

Figure 3 depicts the flowcharts that represent the device drivers implemented for each sensor. As for DHT22, there is a library that can be used with all existing DHT models. Based on this library the DHT22 *readHT* function was implemented to perform a sequential read starting with the relative humidity in percentage and followed by the temperature in degrees celsius.

The SGP30 *readGAS* function allows TVOC, eCO_2, raw H_2 and raw ethanol values to be obtained sequentially. First, it starts by trying to measure the concentration of TVOC and eCO_2. If the measurement fails, it will return an error message. Then, a set of raw measurements, raw H2, and raw ethanol, is performed. After all measurements, a counter is incremented, and if it reaches thirty, a hexadecimal baseline is returned. This value is then used in a function provided by the SGP30 library for calibration purposes. The SGP30 uses a tinny metal-oxide element that, when exposed to organic compounds, changes its electrical resistance [26]. However, due to the variation of the environmental and operational conditions such as temperature and humidity, the resistance baseline changes, which demands a new baseline calibration to enable the measurement of absolute values.

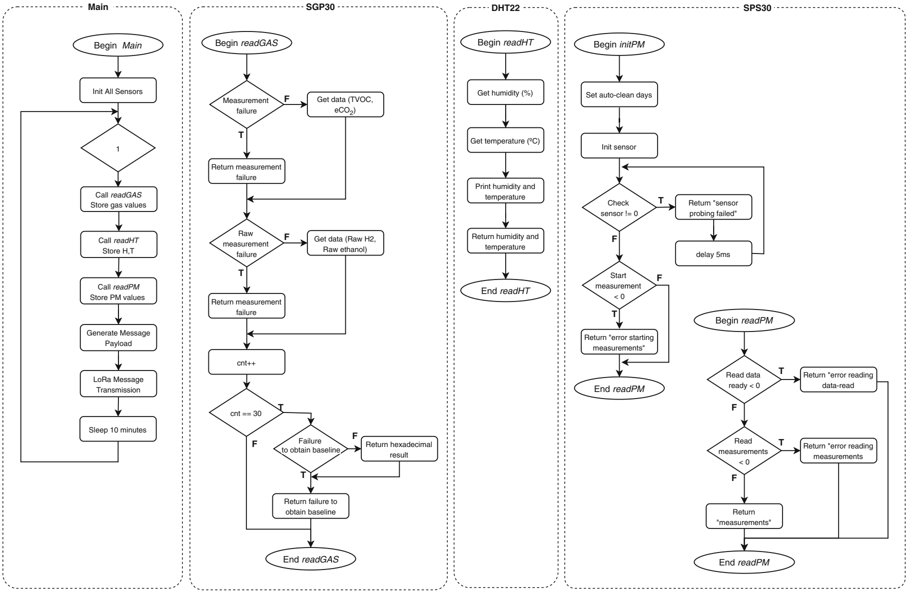

Fig. 3. Embedded firmware flowcharts.

The SPS30 sensor is used to measure particle matter and was configured to communicate with the microcontroller through I2C. Due to its normal operation, the SPS30 sensor accumulates dust inside, which must be released regularly. For this, the *initPM* function starts with the configuration of the number of days that the sensor will use to perform the internal automatic cleaning. The purpose of this initial step is to measure the concentration of particles, which are considered as dust. Finally, the SPS30 is then checked to verify that it is operating correctly. As for the *readPM* function, it aims to read the PM1, PM2.5 and PM10 particle concentrations and return the respective results.

4.3 Prototype

Figure 4 depicts the alpha version of the prototype where is possible to observe, the ESP32 microcontroller, the LoRa radio is below, all the sensors DHT22, SGP30, and the SPS30. Due to the COVID-19 pandemic situation, a PCB-based version was not implemented due to the current restrictions on accessing the laboratory. Nevertheless, at the writing of this paper, a more compact PCB version is being designed to increase the prototype robustness, allowing its evolution to a beta version for easy replication and deployment in classrooms. The dimensions are 95 mm × 70 mm × 35 mm with all components assembled and the total cost of the prototype is approximately 150€.

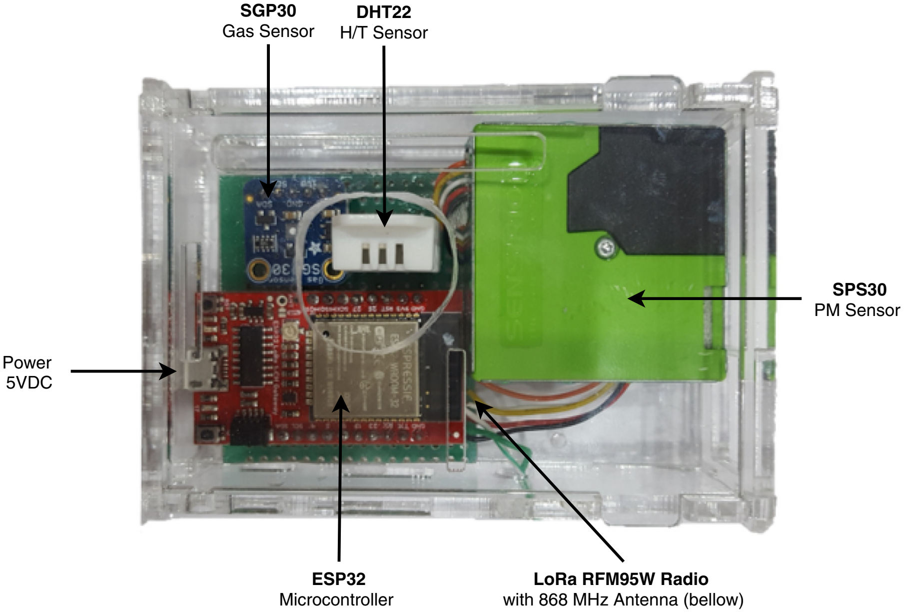

Fig. 4. IoT Edge prototype (Alpha version).

5 Preliminary Results

Due to the current pandemic situation regarding COVID-19, the validation tests had to be carried out at home, more precisely, in a bedroom, with approximately 28 m^2 for 48 h. Figure 5 presents the evolution of the acquired parameters and its relation with some specific annotated events, i.e. cleaning, window opening, and human occupancy. The 48-h average obtained for PM1.0 was around 15 $\mu g/m^3$; for PM2.5 and PM10, the values reached in both approximately 20 $\mu g/m^3$, being within the regulatory limits [18].

These results can be justified by the fact that the room where the data was collected is part of a non-smoking house, as well as that the house is cleaned daily, thus reducing the accumulation of particulate material.

As for the results obtained for VOCs, the measurements never exceeded 50 ppb. One of the tests that were performed, to check the sensor response, consisted of opening a bottle of acetone at a distance of 20 cm from the sensor. The values, after this action, immediately increased to around 150 ppb, not exceeding regulatory limits [18].

Regarding eCO_2, the values were around 400/450 ppm, given that the windows of the space were open. On the other hand, when closed, after some time, the results started to increase around 600/700 ppm, thus not meaning that the air was polluted.

Regarding the temperature and humidity, several measurements were acquired and compared with a digital calibrated hygrometer that was installed in the room. It was observed that the values obtained were in agreement with the sensor tolerance, as introduced in Sect. 4.1.

Fig. 5. Data obtained during a 48 h period in a regularly occupied classroom. The plots are annotated with relevant events, such as window state, outdoor events, number of people in the room and cleanings.

6 Conclusion and Future Work

Today's society organizes much of its daily life in closed spaces, in which IAQ needs to be assessed and managed for improvement. Thus, there are a significant number of health problems, such as asthma, irritation of the eyes, nose, and throat, among others. Schools and school spaces are no exception. In these environments, there is usually no adequate ventilation, in addition to cleaning rooms and offices, sometimes this may not be done daily. This ends up affecting the health, well-being, and success of the educational community.

The accomplishment of this work resulted from the fact that it is essential to obtain low-cost solutions for IAQ management in schools. The proposed IoT Edge device was designed for low-cost IAQ assessment in schools, presenting the ability to acquire several parameters, such as CO_2 equivalent, TVOC, $PM_{1.0}$, $PM_{2.5}$, PM_{10}, temperature, and humidity. The device uses a LoRaWAN network to push data to a cloud-based server and a web-based app with a rich data visualization dashboard generated with the Grafana framework.

Therefore, one of the goals to achieve shortly is related to the activation of a ventilation grid (or system), so that it is possible to effectively improve IAQ in the classrooms when the room is effectively occupied and the IAQ is evaluated as poor. Occupancy detection/counting and IAQ assessment performed together is a challenge and can be done at the edge using a machine learning library, such as Tensorflow Lite, which is specifically implemented to be used in microcontroller-based constrained edge devices [28].

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