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Development of an IoT system for environmental monitoring in SMT lines with ESP32

Development of an IoT system for Environmental Monitoring in SMT Lines with ESP32
Developing an IoT system for environmental monitoring on SMT lines with ESP32

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Abstract. *Controlling environmental conditions in SMT (Surface Mount Technology) Production lines are essential to ensure the quality and reliability of electronic products. Variables such as temperature and humidity directly affect critical processes and may lead to defects, including poor soldering, oxidation, and functional failures. This paper presents the development of an environmental monitoring and control system based on the Internet of Things (IoT), using the ESP32 SoC (System on a Chip) and the DHT22 digital sensor to measure temperature and humidity. The system continuously collects data and transmits it through a broker to a server responsible for real-time visualization. Additionally, alert mechanisms were implemented to indicate conditions outside predefined thresholds. The results demonstrate that the proposed solution improves process reliability by enabling preventive actions and reducing failures related to environmental conditions.*

Abstract. *Controlling environmental conditions in SMT (Surface Mount Technology) production lines is essential to ensure the quality and reliability of electronic products. Variables such as temperature and humidity directly influence critical processes, potentially resulting in soldering defects, oxidation, and functional failures.*
This work presents the development of an environmental monitoring and control system based on the Internet of Things (IoT), using the ESP32 (System-on-Chip) SoC and the DHT22 digital sensor for acquiring temperature and relative humidity data. The system continuously collects data and sends it, via a broker, to a server responsible for real-time visualization. In addition, alert mechanisms were implemented to indicate conditions outside the established parameters. The results demonstrate that the proposed solution contributes to increasing the reliability of the production process, allowing for preventive actions and reducing the occurrence of failures resulting from environmental conditions.

1. Introduction

With the increasing use of embedded systems in industry and the wider dissemination of

The concept of the Internet of Things (IoT) in the context of Industry 4.0.

Solutions based on connected devices are gaining prominence in applications of

Monitoring and automation. The concept of IoT refers to the interconnection of devices.

capable of collecting and exchanging data over the internet, enabling new applications in various fields.

sectors, including the industrial sector (ROSE; ELDRIDGE; CHAPIN, 2015; ATZORI; IERA;

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MORABITO, 2010).

In this scenario, the ESP32 has established itself as a versatile alternative, being widely used.
Used in both simple implementations and more complex systems. Its ease of use
ease of use, *open-source* nature , integrated connectivity via Wi-Fi and Bluetooth, and low
Cost, however, makes the device a recurring choice in IoT projects.

The versatility of the ESP32 is also due to its ability to integrate with different types
of sensors, supported by a robust set of hardware features, such as multiple
communication interfaces (I2C, SPI and UART), analog-to-digital converters (ADCs) and a
A significant number of GPIOs. These features allow for continuous data acquisition.
While maintaining a stable network connection. Native wireless connectivity.
It eliminates the need for external modules, reducing the complexity and cost of the solution.

These characteristics make the ESP32 especially suitable for monitoring applications.
environmental scenarios with low data demand, in which the volume of information
The amount of data transmitted is reduced, as in the periodic reading of temperature and humidity sensors.
In data communication, lightweight protocols such as MQTT are widely used.
IoT applications, enabling the efficient exchange of messages through a model.
publish/subscribe (LIGHT, 2017).

In the context of manufacturing electronic boards using SMT *(Surface Mount* Technology)
(Technology), controlling environmental conditions is a critical factor in ensuring quality.
of the production process. Variables such as temperature and humidity directly influence stages.
such as the application of solder paste and the reflow process, which can cause defects such as
Cold solder joints, oxidation, and functional failures occur when parameters are outside ideal range (LEA, 1997).

Given this scenario, the absence of continuous monitoring or reliance on measurements
manuals can compromise the reliability of the process, making it difficult to identify
Deviations in a timely manner. Thus, the development of solutions becomes relevant.
Automated systems that allow for real-time monitoring of environmental conditions.

In this context, this work proposes the development of a monitoring system for
IoT-based temperature and humidity monitoring, using the ESP32, environmental sensors, and communication.
via a broker and storage in a database. The system allows viewing in
Real-time monitoring of variables, as well as the generation of alerts in case of values outside the ranges.
established limits, which contributes to improved reliability and traceability in
productive environment.

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2. Theoretical Framework

2.1. Industry 4.0 and IoT

The Internet of Things (IoT) represents a technological paradigm based on the interconnection of Physical devices capable of collecting, processing, and transmitting data over the internet. These These devices are typically equipped with sensors, actuators, and communication capabilities. which enables integration with computer systems and process automation.

According to Luigi Atzori, Antonio Iera and Giacomo Morabito (2010), IoT can be understood from three main perspectives: internet-oriented, object-oriented and Oriented towards semantics. In the industrial context, this concept evolves into what is called Industrial. Internet of Things (IIoT), characterized by the application of connected devices in environments. Productive, with a focus on monitoring, controlling, and optimizing operational processes.

In the context of Industry 4.0, IoT-based systems enable continuous monitoring of operational variables, real-time data collection, and decision-making based on More accurate and reliable information. Among its main applications are: Predictive maintenance, production traceability, and environmental monitoring, context in within which this work is included.

The basic architecture of IoT systems is generally composed of three main layers:

- perception layer, responsible for collecting data through sensors and physical devices;
- network layer, responsible for transmitting the collected information;
- application layer, responsible for storage, processing and Data visualization.

The system proposed in this work fits into this architecture by using sensors for the environmental data collection, a Wi-Fi network for information transmission, and an application. web-based real-time monitoring.

2.2 Embedded Systems Applied to Monitoring

Embedded systems are computer systems dedicated to performing specific functions. in larger devices. Unlike general-purpose computers, they have They have limited resources and are designed to operate in isolated contexts (MARWEDEL, 2021).

The ESP32 is a widely used SoC in IoT applications due to the following reasons:

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characteristics:

- Integrated Wi-Fi/Bluetooth connection module;
- low energy consumption;
- multiple communication interfaces;
- Low implementation cost.

Developed by Espressif Systems, the ESP32 features a 32-bit dual-core architecture and GPIOs. Configurable and supportive of communication protocols widely used in projects of automation, such as UART (Universal Asynchronous Receiver-Transmitter, used in serial communication with computers and other devices. microcontrollers; SPI (Serial Peripheral Interface), commonly used in communication with displays and storage modules; and I2C (Inter-Integrated Circuit), widely used for integration with sensors and peripherals. The device also features Analog-to-digital converters (ADCs) allow the reading of analog sensors, making it... suitable for data acquisition and remote monitoring applications (ESPRESSIF SYSTEMS, 2023).

Its application in environmental monitoring systems is common due to its ease of use. Integration with sensors and real-time communication capability.

2.1.3 Temperature and Humidity Sensors

Sensors are devices responsible for detecting physical quantities in the environment and converting them. them in signals interpretable by computer systems. In monitoring applications Environmental control, temperature and humidity sensors are widely used. variables that directly impact industrial processes (FRADEN, 2016).

In this work, the DHT22 digital sensor, also marketed as AM2302, was used. responsible for measuring ambient temperature and relative humidity. The sensor operates through the combination of two main elements: a capacitive sensor for measuring A device uses humidity and a thermistor for temperature measurement. The collected data is processed. internally by a microcontroller embedded in the device itself, which performs the It calibrates the signals and sends the values to the external system via digital communication. single-wire communication (AOSONG ELECTRONICS, 2023).

According to the datasheet from the manufacturer Aosong Electronics, the DHT22 has a measurement range. temperature between -40 °C and 80 °C, with an accuracy of ±0.5 °C, and humidity measurement range. between 0% and 100%.

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The sensor's digital communication reduces interference common in analog sensors.
increasing the reliability of data collection in continuous monitoring applications.
In addition, its low cost, ease of integration with external systems, and accuracy are advantages.
Suitable features make the DHT22 a viable alternative for industrial monitoring applications.
low complexity environmental environment.

In the system developed in this work, the sensor is responsible for the continuous collection of data.
environmental, sending the information to the ESP32 for subsequent transmission to the server of
monitoring.

2.4 MQTT Protocol in IoT Communication

MQTT (Message Queuing Telemetry Transport) is a lightweight communication protocol.
Developed for devices with limited computing resources and low-bandwidth networks.
bandwidth, being widely used in IoT applications. The protocol was created by
Andy Stanford-Clark and Arlen Nipper with the goal of providing an efficient solution for
data transmission between remote devices (LIGHT, 2017).
Unlike traditional request-response based communication models
(Like the HTTP protocol), MQTT uses a publisher/subscriber architecture. In this
In this context, publishing devices send messages to specific topics in
a broker, while subscriber devices automatically receive the
Messages on topics of interest.
The basic architecture of MQTT consists of three main elements:

- Publisher: device responsible for sending the information;
- Broker: an intermediary server responsible for managing messages;
- Subscriber: device or system responsible for receiving the data.

According to the official OASIS specification (2014), the protocol operates over the TCP/IP protocol.
and features characteristics such as low bandwidth consumption, low computational overhead and
High scalability, making it suitable for continuous monitoring applications in
industrial environments.

In the system developed in this work, the ESP32 acts as a publisher, sending
The temperature and humidity data collected by the DHT22 sensor are periodically sent to a broker.
MQTT. Subsequently, this information is forwarded to the server responsible for...
Storage, processing, and real-time visualization.
The use of MQTT in this project was motivated by the need for communication.

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Efficient, reliable, and with low computational cost, suitable for the monitoring scenario.

Continuous environmental impact on SMT production lines.

2.5 SMT Process and Influence of Environmental Conditions

Surface Mount Technology (SMT) is widely used in the manufacture of circuit boards.
electronics due to their ability to increase component density on circuit boards.
Printed circuit boards (PCBs) reduce production costs and increase productivity on a large scale.
In this process, the electronic components are mounted directly onto the surface of the
PCB, eliminating the need for perforations used in older technologies, such as the
through-hole process (ASHOK; SHARMA, 2020).

The SMT process consists of several critical steps, among which the following stand out:

- Applying solder paste (solder paste printing);
- automatic component positioning (pick and place);
- reflow soldering;
- Automated optical inspection (AOI);
- functional tests.

Each of these steps can be impacted by unsuitable environmental conditions.
especially temperature and relative humidity
According to David M. Jacobson and Gopal Hedge in Microelectronics Manufacturing
In Engineering and Technology, inadequate humidity levels can cause absorption.
This moisture affects sensitive components, increasing the risk of failures during the process.
welding, such as the phenomenon known as popcorn, characterized by the internal expansion of
humidity during heating.

Furthermore, high temperatures can compromise the stability of the solder paste.
altering its viscosity and reducing its efficiency during the paste printing process
solder paste printing, while high humidity levels can
accelerate oxidation processes in electronic components and metal surfaces, affecting
directly affects the quality of the welding (LEA, 1997).

According to the IPC standard, especially in documents such as IPC J-STD-033,
Moisture-sensitive components should be stored and used under certain conditions.

Controlled environmental measures to prevent degradation and failures in the production process.

In industrial environments where monitoring is performed manually or in a way
Periodic environmental variations can go unnoticed, increasing the risk of defects and

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rework. In this context, automated continuous monitoring systems become
important for enabling preventive actions and ensuring greater stability to the process.
productive.
The system proposed in this work seeks to act directly in this scenario, carrying out the
Continuous monitoring of ambient temperature and humidity, allowing for greater
Traceability and the prevention of failures resulting from environmental conditions.

3. Development

3.1 General System Architecture

The system developed consists of three main layers: embedded device,
communication and application on the server. The architecture was designed to ensure continuous collection.
data, efficient information transmission, and real-time visualization.
In the acquisition layer, the ESP32-based device is responsible for reading the data.
Environmental data is collected via the DHT22 sensor. This data is displayed locally on a screen.
LCD data is periodically sent to a message broker.
In the communication layer, the RabbitMQ broker was used, responsible for mediating the...
Message exchange between the device and the server.
Finally, at the application layer, a solution was developed consisting of a service.
consumer, responsible for data processing and storage, and for an API.
HTTP is used to make the information available to the end user through a web interface.



Figure 1 – General system architecture.

3.2 Embedded Device Development

3.2.1 Data Collection and Display

The temperature and humidity data is read every 5 seconds by the sensor.
DHT22. The values obtained are displayed immediately on the 16x2 LCD display, allowing the
Real-time local monitoring.

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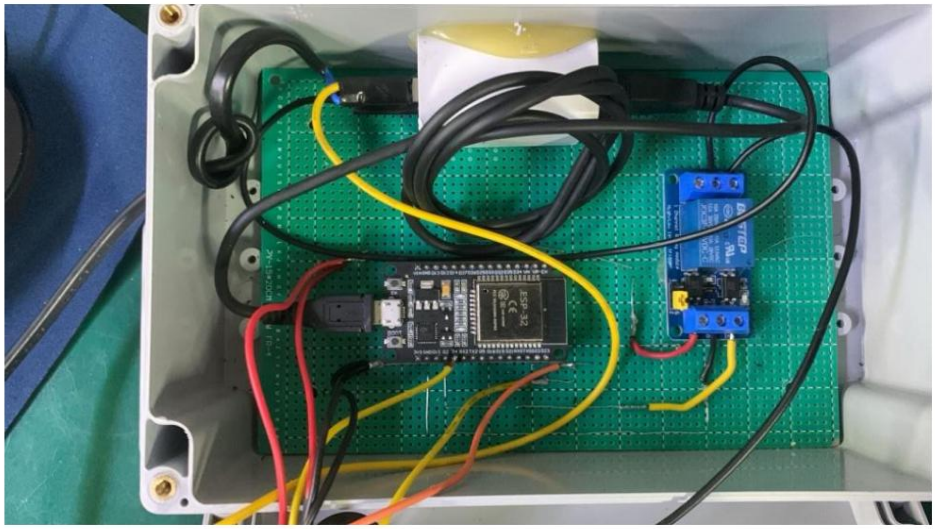


Figure 2 – Physical prototype of the system (internal part).



Figure 3 – Physical prototype of the system (external part).

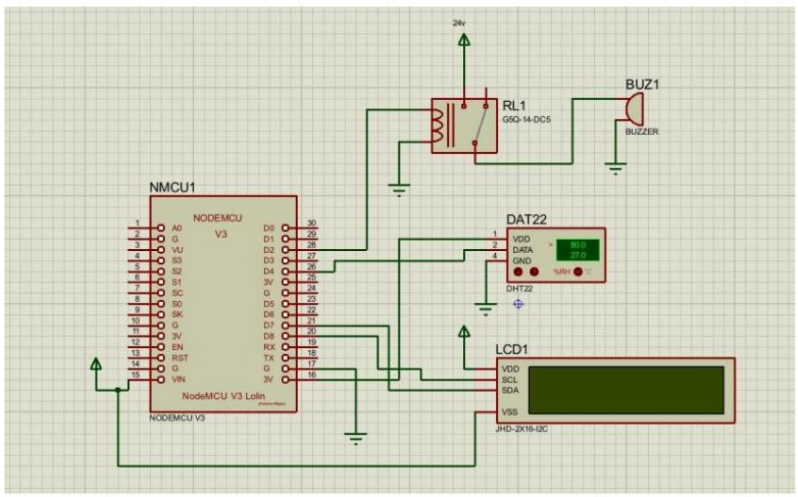


Figure 4 – Electrical diagram of the system.

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The data is sent in a structured format, containing:

- temperature;
- humidity;
- Reading *timestamp ;*
- Device identification.
-

3.2.2 Alert Logic

The system has an alert mechanism based on pre-set operating limits.
defined in the firmware. These limits define acceptable maximum and minimum values of
temperature and humidity.
When the measured values exceed these limits, the system activates a buzzer to signal this.
sonically.

The alert behavior follows this logic:

• The buzzer is activated for 15 seconds;

- After this period, it remains switched off for 1 minute and 30 seconds;
- If the alert condition persists, the cycle is automatically restarted.

This mechanism avoids continuous and excessive alerts, maintaining the effectiveness of the signaling.
without causing operational discomfort.

3.3 Communication System

Communication between the device and the server is carried out through the RabbitMQ broker, which
It acts as an intermediary in the exchange of messages.
The broker runs in a containerized environment using Docker, which simplifies deployment.
and the isolation of services.
The model adopted is based on the publication and consumption of messages, in which:

- The ESP32 acts as *a publisher;*

• The back-end service acts as a consumer.

3.4 Back-end and Data Persistence

The back-end was developed using the ASP.NET platform, and is responsible for both
both the consumption of messages and the provision of data through an HTTP API.

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3.4.1 Consumer Service

A dedicated service acts as a consumer of messages published on the RabbitMQ broker. This service remains in continuous operation, monitoring the message queue. Whenever a new message is received, the data is processed and stored in a... database.

3.4.2 Database Modeling

The persistence structure was designed in a simple and efficient way, consisting of two main entities:

Sensors Table

- ID;
- SensorName;
- MacAddress.

Readings Table

- ID;
- Temperature;
- Humidity;
- CreateDate;
- SensorId (foreign key).

This separation allows for greater flexibility in managing devices and greater traceability of the collected data.

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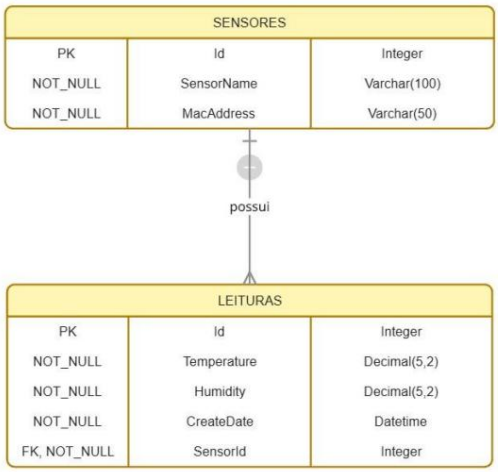


Figure 5 – Entity-relationship diagram.

3.4.3 HTTP API

The back-end application provides an HTTP API for the front-end to consume data.

The following endpoints were implemented:

• **GET /sensors** ÿ returns all registered sensors;

• **GET /sensors/{id}** ÿ returns the details of a specific sensor;

• **GET /sensors/last** ÿ returns the last reading from each sensor;

• **POST /sensors** ÿ allows the registration of new sensors.

Communication between the *controllers* and the business logic is achieved through the following pattern.

Mediator, promoting decoupling and better code organization.

3.5 Web Interface

The front-end was developed using React and Vite, aiming for higher performance during the process.

Development and generation of the application. Tailwind CSS was used for styling.

The main interface features a panel with cards representing the registered sensors.

in the system. Each *card* displays:

- sensor name;
- current temperature;
- current humidity;
- condition status (normal or alert).

The data is obtained through API endpoints and updated dynamically.

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The system includes a reporting screen that allows for historical analysis of the collected data.



Figure 6 – Reports screen.

3.6 Execution Environment

All system components have been configured to run in an environment.
containerized using Docker, including:

- broker RabbitMQ;
- back-end application;
- front-end application;
- Customer service.

This approach simplifies deployment, standardizes the execution environment, and improves...
scalability of the solution.
Ultimately, the proposed architecture ensures continuous collection, efficient processing, and...
Real-time visualization of environmental data. Integration between hardware and software.
It allows for greater control over the conditions of the production environment, which directly contributes to...
the reliability of the process.

4. Results Obtained

The system tests were carried out in three distinct environments: (i) production line, (ii) dry
box and (iii) solder paste storage refrigerator. For the analysis, a
representative sensor for each environment, considering that the system was implemented in
multiple points of the plant.
Each environment has specific operating characteristics, with different acceptable ranges.
temperature and humidity. Despite this, the application maintained the same behavior in

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all scenarios, with readings every 5 seconds, data transmission every 1 minute, and application.
based on the same alert logic as previously defined limits.

4.1 Analysis by Environment

The analysis of the results was performed considering the behavior of the sensors in each
environment, focusing on the stability of readings and the occurrence of alerts.
In the production line, greater variation in temperature and humidity was observed throughout the process.
time, which is expected due to the direct influence of the factory environment. As a consequence,
There was a higher incidence of activations of the alert mechanism.
In a dry box environment, characterized by strict humidity control, the values
They remained more stable throughout the analyzed period, with a low occurrence of deviations.
in relation to the established limits.
In the solder paste storage refrigerator, the temperature values showed...
little variation, remaining within a narrow range, while humidity showed
Behavior compatible with a refrigerated environment.

4.2 Comparison with Reference Sensor

To validate the measurements, a comparison was made between the values obtained by the sensor.
DHT22 and those of a commercial sensor previously used in the production process.
The two sensors were positioned in the same environment, allowing for the simultaneous collection of data.
data and a direct comparison of temperature and humidity values.



Figure 7 – Comparison between the developed sensor and the commercial one.

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The data analysis demonstrated that the values obtained by the developed system presented...
Consistent behavior in relation to the reference sensor, following the variations.
environmental changes over time.
The differences observed between the sensors were specific and remained within a range.
acceptable for environmental monitoring applications, without compromising the use of
proposed system.

4.3 Alert Frequency

Another aspect analyzed was the frequency with which the warning mechanism was activated in each environment.

It was observed that environments with greater variability, such as the production line, presented
The highest number of alerts was reported, while controlled environments, such as dry boxes, showed fewer.
incidence of alerts.

This behavior demonstrates that the system responds appropriately to variations.
environmental conditions and identifies conditions that are outside established limits.

4.4 Considerations Regarding System Performance

The results obtained indicate that the system was able to perform the collection, transmission, and...
Continuous and reliable data storage across all analyzed environments.

The adopted architecture proved to be stable, maintaining data integrity and allowing
View it in real time through the web interface.
Furthermore, the use of configurable limits for each environment allowed for adaptation.
adapting the system to different operating scenarios while maintaining the effectiveness of the alert mechanism.

Final Considerations

This work presented the development of an environmental monitoring system.
Based on the Internet of Things (IoT), using the ESP32 in conjunction with the DHT22 sensor,
with the aim of monitoring, in real time, the temperature variables and
Humidity in SMT production environments.
The proposed solution integrated different technological layers, including a device.
embedded system, communication via RabbitMQ broker, and a server application developed in

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ASP.NET, enabling continuous data collection, processing, and visualization through from a web interface.

The results obtained demonstrated that the system is capable of operating stably in different environments, including the production line, the dry box, and the storage refrigerator. solder paste. The data analysis showed that the reading behavior aligns with specific characteristics of each environment, which validates the system's ability to adapt. under different operating conditions.

Comparison with a commercial reference sensor indicated that the values obtained by The developed system exhibits consistent behavior, reinforcing its reliability. Solution for environmental monitoring applications.

Furthermore, the implemented alert mechanism proved effective in identifying conditions outside the established limits, contributing to quick decision-making and to Preventing failures in the production process.

Its main contribution is the implementation of a low-cost solution. Scalable and easy to integrate, capable of replacing or complementing commercial systems. existing ones, offering greater flexibility and control over the data collected.

For future work, the following is suggested:

- Implementing dynamic configuration of operating limits via a web interface;
- Expanding the system to monitor multiple environmental variables;
- Integration with existing industrial systems, such as MES (Manufacturing Execution). Systems);
- Applying predictive analytics techniques to the collected data.

Therefore, it can be concluded that the developed system meets the proposed objectives. presenting itself as a viable alternative for environmental monitoring in environments industrial processes, contributing to improved reliability and quality. productive.

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