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Full Length Article

Digital Twin Based Smart Building Management System

Mrs. M. Sandhya Rani[1], Mahima Tennyson[2], Madhu[3], Aravind[4], Chandra sekhar[5]
[1]Assistant Professor; Department of Electronics and Communication Engineering, Lords Institute of Engineering and Technology, Hyderabad, Telangana, India.
[2,3,4,5]B.E.Students; Department of Electronics and Communication Engineering, Lords Institute of Engineering and Technology, Hyderabad, Telangana, India.
Corresponding Author Email: sandhya.m@lords.ac.in

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Abstract:
Transforming smart building management into a digital twin technology is operational efficiency and safety enhancement. This paper presents a digital smart building management system comprising an Raspberry Pi Model designed to successfully achieve communication between sensors and device-related activities. Focused features include gas detection alerts, theft detection based on vibration, air quality monitoring (MQ135), occupancy detection (IR sensors), adaptive lighting control (LDR), and temperature/humidity control via DHT11. Early hazard detection is ensured from fire sensors.
Real-time data processing with ThingSpeak integrated it contributed to continuous real-time monitoring. Emergency response would thus use a GSM module. The L293D driver controlled ventilation with both a CPU fan and DC motor. Feedbacks are relayed via real time on an oLED display too. This is a truly reliable, efficient, and safe building management system made possible through integrating digital twin technology with an IoT-based automation mechanism.

Keywords— *Digital Twin, Smart Building Management, Internet of Things (IoT), Raspberry Pi, Real-Time Monitoring, Building Automation, ThingSpeak, GSM Communication.*

Introduction:

The rapid growth of urban infrastructure and the increasing demand for energy-efficient, secure, and intelligent buildings have accelerated the adoption of smart building technologies. Conventional Building Management Systems (BMS) primarily rely on standalone monitoring and control mechanisms, which often lack real-time synchronization, predictive capabilities, and centralized decision-making. As buildings become more complex, there is an increasing need for intelligent management platforms capable of continuously monitoring environmental conditions, optimizing resource utilization, and ensuring occupant safety. In recent years, **Digital Twin (DT)** technology has emerged as a promising solution by creating a virtual representation of physical assets that continuously exchanges real-time data with the physical environment. This bidirectional communication enables efficient monitoring, simulation, fault prediction, and operational optimization, making digital twins an essential component of next-generation smart building management systems **[1]**.

Digital Twin technology integrates sensing devices, communication networks, cloud computing, and intelligent analytics into a unified framework that enables continuous monitoring of building infrastructure. Unlike conventional automation systems, a digital twin maintains a dynamic virtual model of the physical building by collecting real-time information from embedded sensors and connected devices. This virtual model enables facility managers to observe building performance remotely, evaluate system behavior, identify abnormal operating conditions, and perform predictive maintenance before equipment failure occurs. Such capabilities significantly improve operational efficiency while minimizing maintenance costs and energy consumption **[2]**.

Modern smart buildings require continuous monitoring of various environmental and security parameters to ensure safe and comfortable living conditions. Environmental factors such as indoor air quality, temperature, humidity, gas leakage, smoke, fire hazards, lighting conditions, and occupancy directly influence both occupant well-being and building performance. Recent advancements in Internet of Things (IoT) technology have enabled the deployment of multiple low-cost sensors capable of continuously monitoring these parameters. By integrating these sensing devices with embedded controllers such as the Raspberry Pi, building management systems can automatically respond to environmental changes while reducing the need for manual supervision. The combination of IoT and

Digital Twin technology therefore provides an intelligent platform for efficient building automation and real-time decision-making **[3]**.

Energy management has become another critical aspect of smart building development due to increasing energy demand and environmental sustainability concerns. Intelligent control of lighting, ventilation, heating, and cooling systems contributes significantly to reducing electricity consumption while maintaining occupant comfort. Digital Twin technology supports adaptive energy management by continuously analyzing operational data and dynamically controlling building resources according to actual environmental conditions. Real-time simulation further enables optimization of energy utilization and facilitates data-driven decision-making for sustainable building operation **[4]**.

Recent studies have also emphasized the importance of integrating Digital Twin technology with cloud-based IoT platforms for continuous monitoring and intelligent analytics. Cloud services such as ThingSpeak provide secure storage, visualization, and remote accessibility of sensor data, allowing facility managers to supervise building performance from any location. The integration of cloud computing with Digital Twin models further supports historical data analysis, predictive maintenance, and automated reporting, thereby improving operational transparency and long-term infrastructure management **[5]**.

Building safety remains one of the primary objectives of intelligent building management systems. Modern buildings require immediate detection of hazardous conditions such as combustible gas leakage, poor indoor air quality, unauthorized intrusion, and fire incidents. The integration of gas sensors, vibration sensors, infrared occupancy sensors, fire sensors, and GSM communication modules enables automatic emergency notifications whenever abnormal conditions are detected. Such intelligent safety mechanisms reduce response time during emergencies and significantly enhance occupant protection while minimizing potential property damage **[6]**.

Motivated by these technological advancements, this research proposes a Digital Twin Based Smart Building Management System using a Raspberry Pi platform integrated with multiple environmental and security sensors. The proposed system continuously monitors gas leakage, air quality, occupancy, temperature, humidity, lighting conditions, fire hazards, and vibration-based intrusion while transmitting real-time data to the ThingSpeak cloud platform. The Digital Twin framework enables continuous synchronization between the physical building and its virtual representation, providing remote monitoring, intelligent control, and timely emergency notifications through GSM communication. The proposed system aims to improve building safety, operational efficiency, energy management, and overall occupant comfort through the seamless integration of Digital Twin technology, IoT-based sensing, and intelligent automation **[7]**.

Literature Review:

Tao and Zhang introduced the concept of the Digital Twin Shop-Floor as a new paradigm for intelligent manufacturing by establishing continuous interaction between physical assets and their virtual counterparts. Their work demonstrated that real-time synchronization allows efficient monitoring, fault diagnosis, predictive maintenance, and optimized operational control. The proposed digital twin architecture laid the foundation for applying virtual simulation technologies beyond manufacturing, including intelligent infrastructure and smart building management systems. **[1]**

Nie, Xu, Cheng, and Yu proposed a Digital Twin-based smart building management and control framework that integrates sensing devices, communication networks, and virtual building models for real-time supervision. Their framework emphasized the importance of continuous data synchronization between physical infrastructure and digital models to improve operational efficiency, resource utilization, and intelligent decision-making. The study demonstrated that digital twin technology significantly enhances remote monitoring and adaptive building control. **[2]**

Liu, Wu, and Long investigated the application of Digital Twin technology in building operation and maintenance management. Their research highlighted that real-time monitoring of building assets enables early fault identification, predictive maintenance, and optimized facility management. The proposed approach reduced maintenance costs while improving equipment reliability through continuous synchronization between physical systems and digital representations. **[3]**

Zhao focused on the development of a smart building energy management system using Digital Twin technology. The proposed model continuously analyzed energy consumption patterns and dynamically controlled building resources to improve energy efficiency. The research demonstrated that integrating real-time monitoring with intelligent control algorithms effectively minimizes unnecessary energy usage while maintaining occupant comfort and supporting sustainable building operation. **[4]**

Piras, Agostinelli, and Muzi presented a case study on integrating Digital Twin technology with IoT-enabled smart buildings to monitor environmental conditions and workplace wellness. Their work demonstrated that continuous acquisition of sensor data improves indoor environmental quality by enabling efficient management of lighting, ventilation, thermal comfort, and air quality. The study concluded that data-driven decision-making contributes significantly to occupant well-being and operational efficiency. **[5]**

Vijayan, Thirisha, Kumar, Yuvaraju, Revathi, and Rehman developed a Digital Twin-based smart building and energy management framework that integrates IoT devices with intelligent monitoring algorithms. Their proposed architecture provided real-time visualization of building performance while enabling automated control of energy-consuming equipment. The study highlighted the effectiveness of combining Digital Twin technology with embedded systems for achieving energy-efficient and secure smart building environments. **[6]**

Wang proposed a Digital Twin-based smart energy monitoring and management system capable of continuously supervising energy utilization within intelligent buildings. The research emphasized real-time acquisition of operational data, intelligent energy analysis, and predictive optimization for reducing energy wastage. The proposed framework demonstrated improved operational efficiency through adaptive control strategies and continuous monitoring of electrical resources. **[7]**

Deng, Menassa, and Kamat presented a comprehensive review describing the evolution from Building Information Modeling (BIM) to Digital Twin technology in the Architecture, Engineering, Construction, and Facility Management (AEC-FM) industry. Their study explained how Digital Twins extend conventional BIM by incorporating live sensor data, bidirectional communication, and intelligent analytics. The review identified Digital Twin technology as a critical component for future smart building operation, predictive maintenance, and lifecycle management. **[8]**

Fuller, Fan, Day, and Barlow reviewed the enabling technologies, research challenges, and future opportunities associated with Digital Twin systems. Their work identified the importance of Internet of Things devices, cloud computing, artificial intelligence, and data analytics in developing intelligent Digital Twin environments. The authors also discussed several implementation challenges, including interoperability, cybersecurity, scalability, and real-time data synchronization, which remain active research areas for future smart infrastructure development. **[9]**

Rasheed, San, and Kvamsdal examined the fundamental values, implementation challenges, and technological enablers of Digital Twin systems from a modeling perspective. Their study highlighted the importance of accurate mathematical modeling, continuous sensor integration, and real-time simulation in improving system reliability and predictive capability. The authors concluded that Digital Twin technology offers significant benefits for intelligent monitoring, operational optimization, and predictive maintenance across multiple engineering domains, including smart buildings. **[10]**

Proposed System:

The proposed system uses a digital twin—a virtual replica of the physical building—integrated with IoT sensors to provide real-time data and intelligent control. It enables continuous monitoring, analysis, and simulation of building operations such as energy usage, equipment health, and occupant comfort. The digital twin allows facility managers to predict issues, optimize performance, and make data-driven decisions, leading to smarter, safer, and more efficient building management.

Methodology

The proposed Digital Twin-Based Smart Building Management System adopts an IoT-enabled embedded architecture for real-time monitoring, intelligent control, and remote building supervision. The methodology integrates multiple environmental and security sensors with a Raspberry Pi microcontroller, ThingSpeak cloud platform, and Digital Twin technology to improve building safety, energy efficiency, and operational reliability.

Initially, the regulated power supply energizes the Raspberry Pi and all connected sensing modules. The system then initializes the DHT11 temperature and humidity sensor, gas sensor, MQ-135 air quality sensor, vibration sensor, IR occupancy sensor, LDR, and fire sensor to continuously acquire environmental and security-related data.

The Raspberry Pi collects and processes the sensor readings by comparing them with predefined threshold values. Under normal conditions, the measured parameters are displayed on the OLED display and transmitted to the ThingSpeak cloud platform through the IoT communication network. The cloud platform continuously updates the Digital Twin model, providing a virtual representation of the building for remote monitoring and data analysis.

Whenever abnormal conditions such as gas leakage, poor air quality, fire, unauthorized intrusion, or unusual vibration are detected, the Raspberry Pi immediately activates the corresponding control mechanisms. The driver circuit operates connected loads such as ventilation fans and lighting systems, while the GSM module sends instant alert messages to the building administrator for emergency response. The LDR sensor enables automatic lighting control based on ambient light intensity, thereby improving energy efficiency.

The entire system operates in a continuous monitoring cycle, where sensor data are synchronized with the Digital Twin model in real time. Historical data stored on the cloud platform support trend analysis, predictive maintenance, and informed decision-making. The integration of embedded sensing, IoT communication, ThingSpeak, and Digital Twin technology provides an efficient, reliable, and scalable solution for intelligent smart building management.

Block diagram:

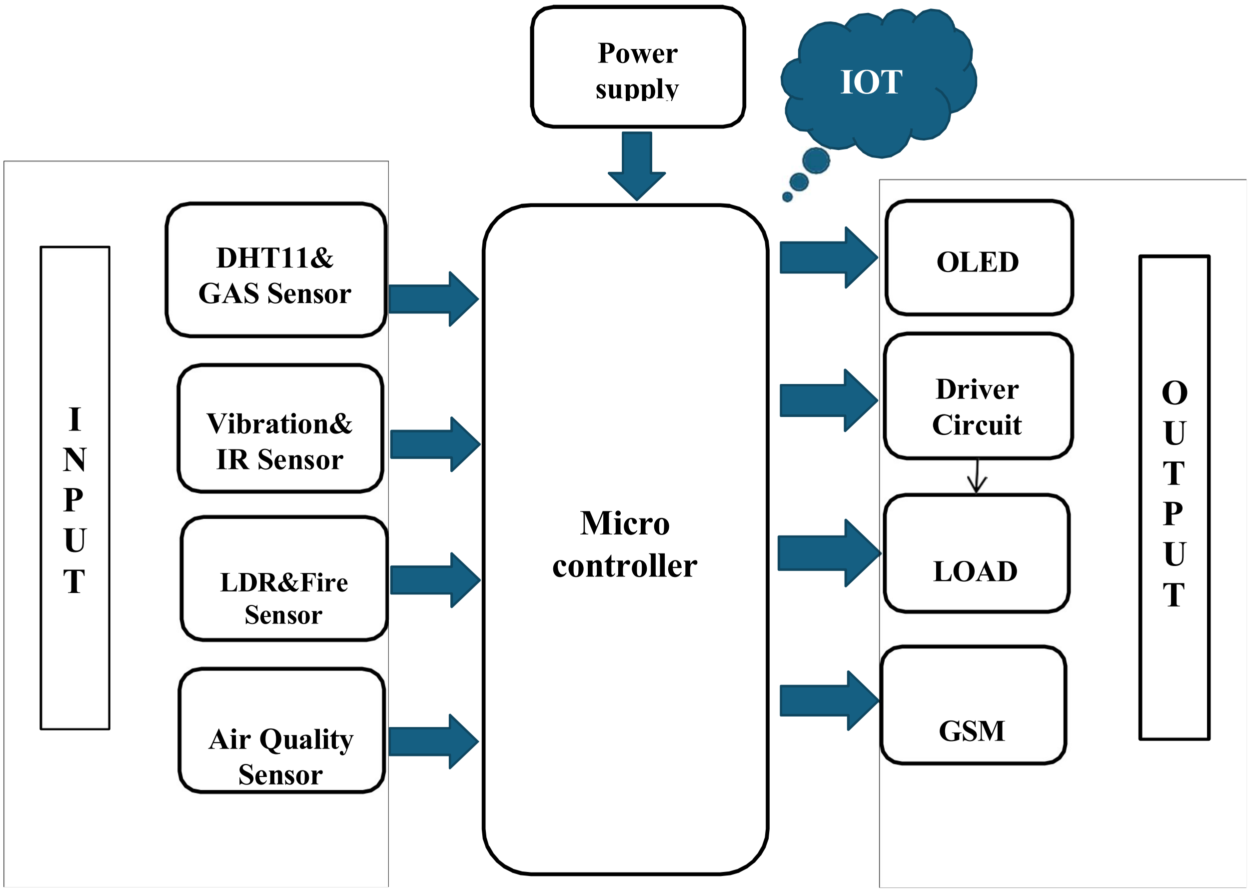


Figure .1: Block diagram

Working Process

The proposed Digital Twin-Based Smart Building Management System is designed to provide continuous monitoring, intelligent automation, and real-time control of building environments through the integration of IoT-enabled sensors, a Raspberry Pi microcontroller, cloud connectivity, and Digital Twin technology. The operational workflow of the proposed system is explained as follows.

Initially, the regulated power supply energizes the Raspberry Pi microcontroller and all sensing modules. After system initialization, the controller establishes communication with the IoT platform and verifies the operational status of each sensor before commencing the monitoring process.

The **DHT11 sensor** continuously measures the indoor temperature and relative humidity, while the **gas sensor** monitors the presence of combustible or harmful gases. At the same time, the **air quality (MQ-135) sensor** evaluates indoor air quality by detecting pollutants such as carbon dioxide, ammonia, and smoke. The **vibration sensor** detects unauthorized access or abnormal structural vibrations, whereas the **IR sensor** identifies human occupancy inside the building. In addition, the **LDR sensor** measures ambient light intensity for automatic lighting control, and the **fire sensor** continuously monitors for flame or fire incidents.

All sensor data are collected and processed by the Raspberry Pi in real time. The measured values are compared with predefined threshold limits stored within the controller. Under normal operating conditions, the current environmental parameters and system status are displayed on the OLED display for local monitoring. The collected data are simultaneously transmitted to the IoT platform, where a Digital Twin model continuously updates the virtual representation of the building and enables remote monitoring through real-time visualization.

Whenever any environmental parameter exceeds its permissible limit, the controller immediately initiates appropriate control actions. If hazardous gas leakage or poor air quality is detected, the driver circuit activates the ventilation system to improve indoor air circulation. During fire detection, the system generates an emergency alert while simultaneously notifying the building administrator through the GSM communication module. Similarly, unauthorized entry detected by the vibration or IR sensor triggers an instant security notification. The LDR sensor automatically controls lighting based on ambient illumination, thereby reducing unnecessary energy consumption.

The driver circuit controls connected electrical loads such as exhaust fans, lighting systems, and emergency devices according to the decisions made by the controller. Simultaneously, alert messages and sensor readings are displayed on the OLED module, allowing occupants to monitor the current building conditions locally. Important events and sensor measurements are continuously uploaded to the IoT cloud platform, enabling the Digital Twin model to maintain real-time synchronization between the physical building and its virtual counterpart.

The entire monitoring and control process operates continuously in a closed-loop manner. As environmental conditions change, the Digital Twin receives updated sensor information, allowing facility managers to observe building performance remotely, analyze historical data, identify abnormal conditions, and take preventive actions before failures occur. This integration of embedded sensing, IoT communication, Digital Twin technology, and intelligent automation enhances building safety, improves energy efficiency, minimizes maintenance requirements, and provides reliable real-time building management.

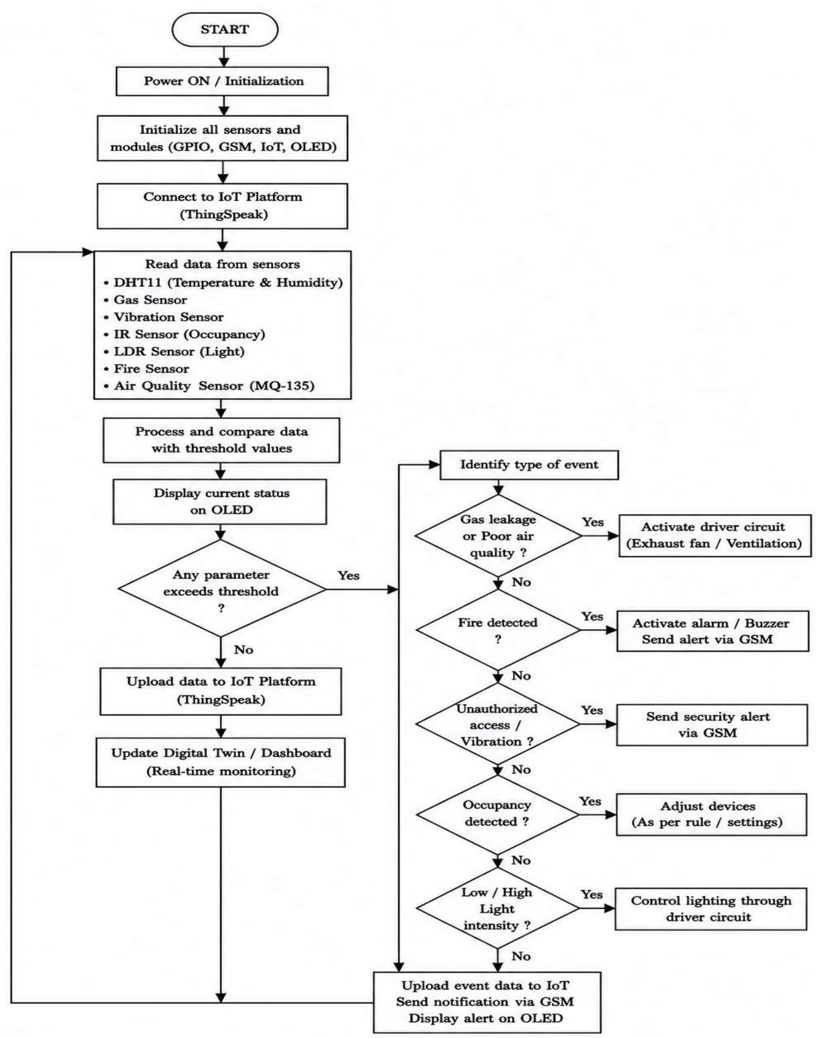


Figure 2 : Working Flow

Schematic Diagram:

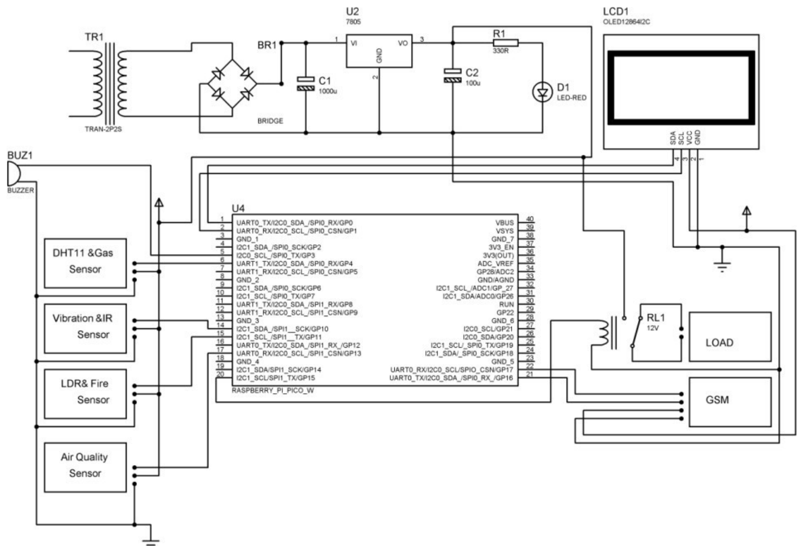


Figure .3: Schematic diagram

Result:

The Digital Twin Based Smart Building Management System was successfully developed and tested to provide intelligent monitoring, automation, and safety management for modern buildings. The system effectively uses sensors such as the DHT11 sensor, MQ135 and MQ2 gas sensors, IR sensor, vibration sensor, LDR sensor, rain sensor, and fire sensor to continuously monitor environmental conditions, security status, and building operations.

The system responded accurately by detecting occupancy, monitoring temperature, humidity, air quality, fire hazards, rainfall conditions, and unauthorized vibrations, while providing alerts or automatic control actions whenever required. The integration of Raspberry Pi Pico W, ThingSpeak IoT platform, GSM module, OLED display, relay modules, and automated devices ensured real-time communication, remote monitoring, and efficient system control.

Overall, the system demonstrated reliable performance, enhanced building safety, improved energy efficiency, and reduced the need for constant manual supervision. The synchronization of real-time data with the digital twin model made it an effective and practical solution for smart building automation, predictive maintenance, and intelligent facility management.

Outputs:

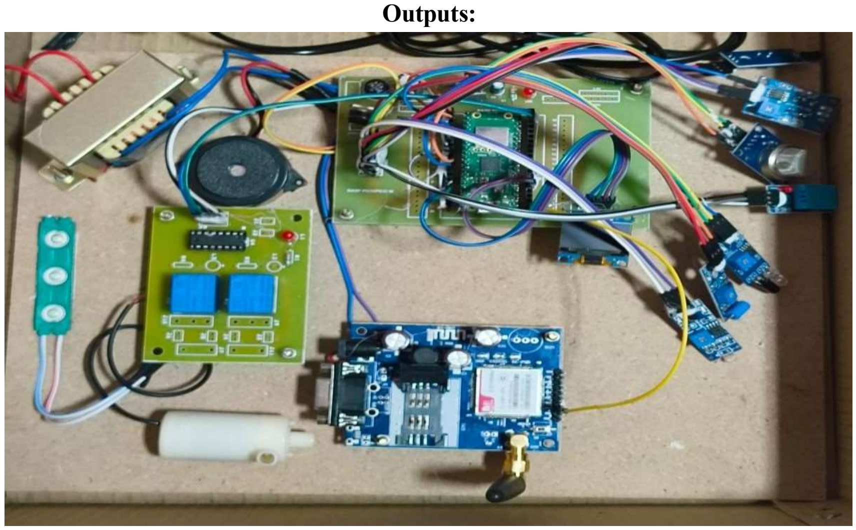


Figure 4: Hard ware kit

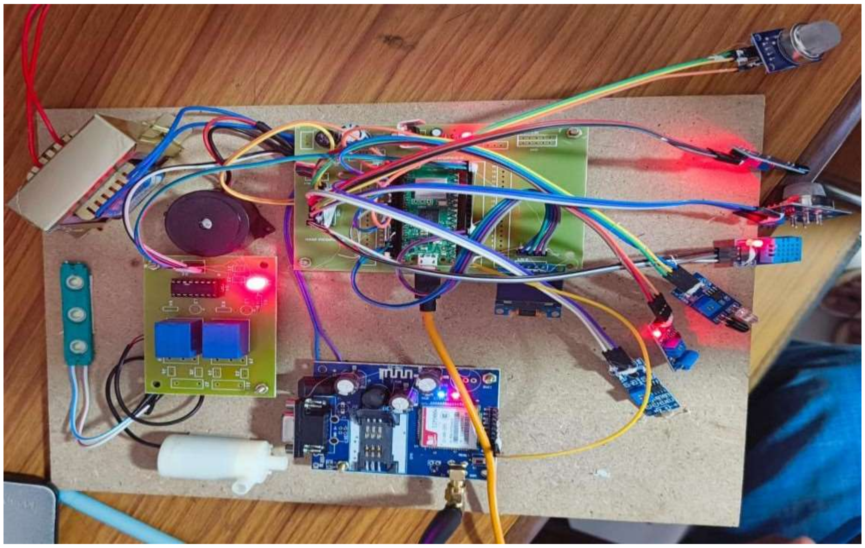
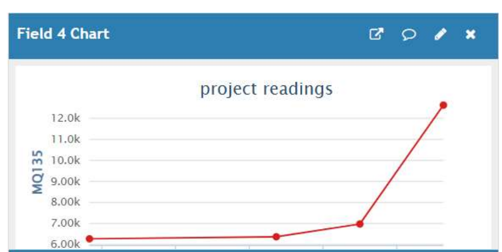
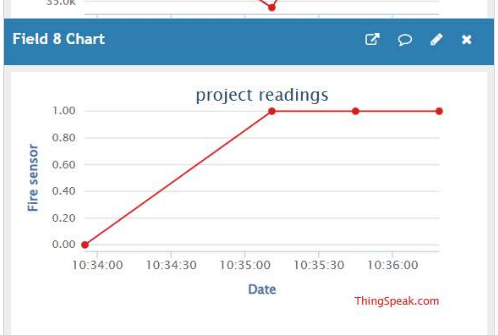


Figure 5: Hardware kit ON state





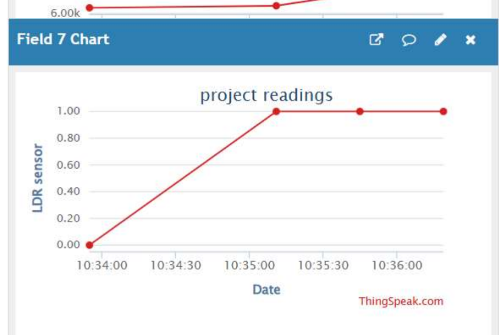


Figure 6: Outputs in Thingspeak

Future Scope:
In the future, the system can be enhanced with AI-based analytics to predict equipment failures, optimize energy consumption, and automatically improve building operations based on occupancy patterns and environmental conditions. Integration with mobile applications and cloud platforms can allow facility managers to monitor real- time data such as temperature, humidity, air quality, security status, and energy usage from anywhere. Advanced sensors such as smart cameras, biometric access modules, and structural health monitoring devices can be added to improve safety, surveillance, and infrastructure management.
Additionally, the smart building system can be connected to broader smart city ecosystems for coordinated control of energy grids, water management, traffic systems, and emergency services. Features like predictive maintenance alerts, intelligent evacuation guidance during emergencies, renewable energy optimization, and integration with solar panels or EV charging stations can further improve sustainability and efficiency. Overall, the Digital Twin Based Smart Building Management System can evolve into a fully intelligent, autonomous infrastructure solution that enhances convenience, safety, operational efficiency, and environmental sustainability.

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